NC Transportation Center of Excellence on Connected and Autonomous Vehicle Technology (NC-CAV)

https://www.nccav.com/

North Carolina Agricultural and Technical State University

NC STATE UNIVERSITY

UNC CHARLOTTE

STATE OF NORTH CAROLINA DEPARTMENT OF TRANSPORTATION

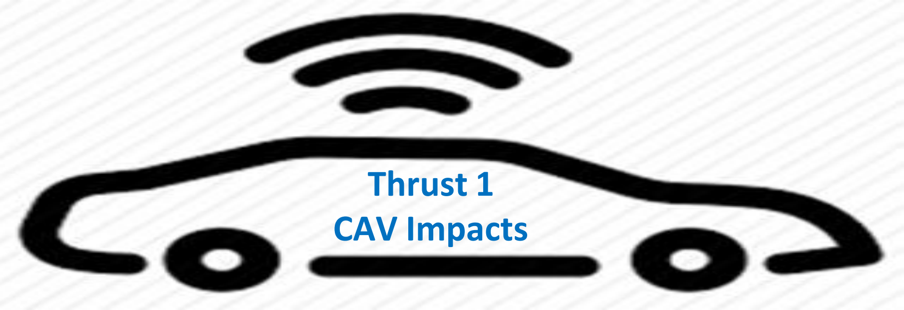
TCE2020-03

Annual Meeting
March 18, 2021

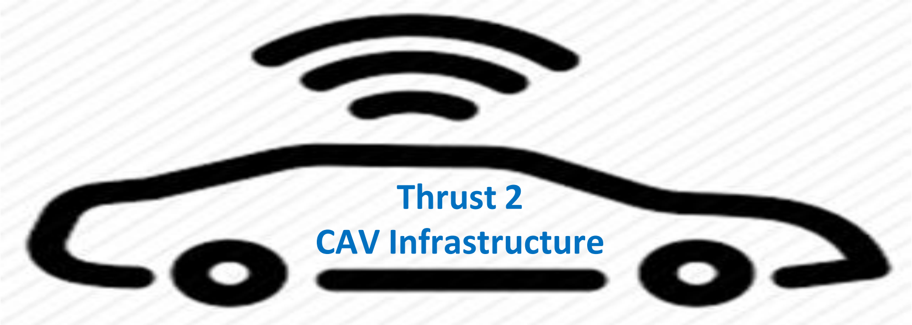
The NC-CAV Center of Excellence

NC-CAV brings together a strong and diverse team of NCAT, NCSU, and UNCC to conduct an innovative, cutting-edge, synergistic, interdisciplinary research on connected autonomous vehicles which will prompt revolutionary transformations in the transportation systems by providing increased capacity, reliability, affordability, and sustainability.

NC-CAV Research Thrusts



Thrust 1 investigates the impact of Connected and Autonomous Vehicles (CAV) on North Carolina's transportation system, and associated revenue.



Thrust 2 assesses North Carolina’s readiness for CAVs in terms of traditional and emerging transportation infrastructure.

Thrust 3 explores emerging applications of CAVs and develops and deploys CAVs and Unmanned Aerial Vehicles (UAVs) for advancing transportation systems.

Outline

- Progress review: Project 1: CAV Impacts on Traffic Intersection Capacity and Transportation Revenue
- Progress review: Project 2: Assessing North Carolina Readiness for CAVs in Traditional and Emerging Infrastructure Needs
- Progress review: Project 3: Developing and Implementing CAV-UAV Collaboration for Advancing the Transportation Systems
- NC-CAV Integration and Demonstration
- NC-CAV Education and Outreach
- NC-CAV Research Dissemination Activities
- NC-CAV Sustainability Activities
- Questions

NC Transportation Center of Excellence on Connected and Autonomous Vehicle Technology (NC-CAV)

Project 1

CAV Impacts on Traffic Intersection Capacity and Transportation Revenue

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Research Background

- The emergence of CAVs in North Carolina will have a profound influence on the performance of our current transportation system.

- Current Highway Capacity Manual (HCM) methods do not consider the role of CAVs - evaluating the capacity of intersections is becoming a critical issue to be resolved for traffic engineers and transportation planners.

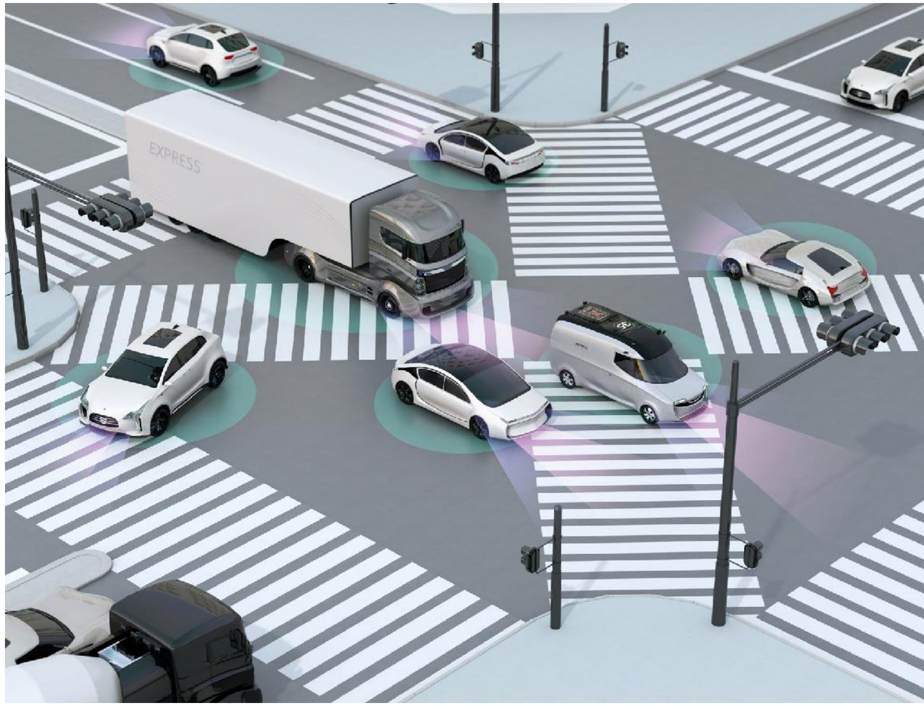
- CAVs are also expected to have significant impacts on the economic outlook of North Carolina (e.g., motor fuel taxes, sales and use taxes, toll receipts, moving violation fines, DMV fees, parking revenue, and other revenue sources) that need to be evaluated.

Research Thrust 1: CAV Impacts

Project 1: CAV Impacts on Traffic Intersection Capacity and Transportation Revenue
Principal Investigator: W. Fan (UNCC)
Other Investigators: NCAT: S. Jiang; ITRE: A. Hajbabaie, D. Findley, S. Bert, N. Norboge, L. Song
Scope: Thrust 1 investigates impacts of CAVs on the transportation system's performance, particularly on intersection capacity adjustments while accounting for mixed vehicle fleets with different levels of CAV adoption. This project will also assess the fiscal revenue impacts of the transition to CAVs on North Carolina's cities, towns, and households.

Objectives:

- Surveying CAV technologies and their impacts on intersection capacity and the associated transportation revenues;
- Develop case studies to illustrate the impacts of CAVs on the traffic systems, particularly at the intersections, suitable intersections will be identified for the case study;
- Analyze the impacts of the CAV technologies on intersection capacity and provide recommendations for future research directions;
- Analyzing the revenue impacts and opportunities of deployment of CAVs at various adoption rates and policy scenarios in NC.



Project 1 Research Tasks and Timeline

Center Admin Activities		FY 2020												FY 2021												FY 2022											
Task	Description	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan
1	Literature Review																																				
2	Identify Potential Intersections																																				
3	Design Scenarios for the Conduct of Simulation																																				
4	Use Simulations to Examine the Established Modeling Framework																																				
5	Develop Guideline on the Intersection Capacity Adjustments Considering Different Level of CAV Penetration																																				
6	Conduct a Revenue Impact Analysis and Propose New Methods																																				
7	Document Research Findings and Develop a Final Report																																				
8	Project Management Activities																																				

Research Task 1: Literature Review

Recent Progress on the Literature Review

- ❖ Concepts and Potential Benefits
- ❖ Deployment of and Market Forecast for AVs
- ❖ Traffic Flow Controls of CAVs
- ❖ Intersection Capacity Analysis Methods
- ❖ Intersection Modeling Scenarios and Parameters

Research Task 1: Literature Review

Concepts and Potential Benefits

According to the NHTSA, CV technologies have the potential to decrease about 80 % of non-injury vehicle crashes (USDOT, 2020).

Table 1 Safety benefits and maturity of CV technologies

Type	Technology	Safety Benefits	Safety Improvement	Maturity
V2I	Red light warning	Warning for red light	High	High
V2I	Stop gap assist	Warning for minimum stop gap	Medium	High
V2I	Reduce speed warning	Warning for speeding	Medium	High
V2I	Traffic Signal Coordination	More benefit for intersection capacity	Low	Medium
V2V	Lane Change Warning	Lane change information from CVs	High	High
V2V	Forward Collision Warning	Avoid Rear-End crashing	High	High
V2V	Electronic Emergency Brake Light	Avoid Rear-End crashing	High	High
V2V	Left Turn Assist	Opposite direction	High	Medium
V2V/V2I	Do Not Pass Warning	Opposite direction	High	High
V2V/V2I	Intersection Movement Assist	Junction crossing	High	Medium
V2V/V2I	Blind Spot Warning	Avoid traffic collision due to the blind spot	High	Medium
V2V/V2I	Emergency Vehicle Priority	Give priority to the emergency vehicle	High	High
V2X	Pedestrian Crossing Warning	Notification of pedestrian crossing the street	High	Low

Concepts and Potential Benefits

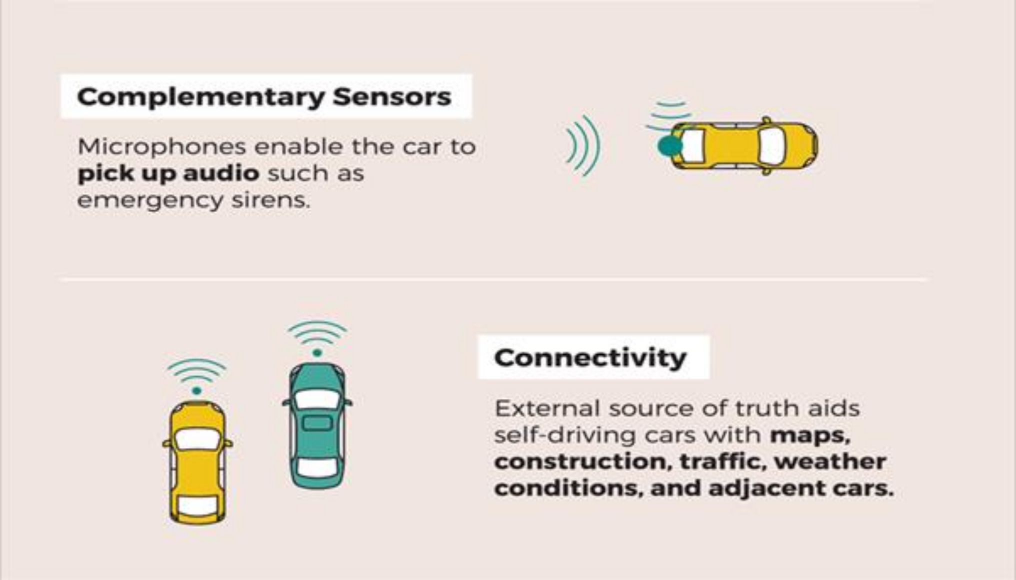
Table 2 Benefits and maturity of autonomous vehicle technologies

	Technology	Safety Benefits	Safety Improvement	Maturity
Level 0	Adaptive headlights	Improve light condition and visibility of environment	Intermediate	High
	Forward collision warning	Prevent rear-end collision	High	High
	Blind spot monitoring	Reduce crash risk caused by blind spots (such as merging and weaving areas)	High	High
	Traffic sign recognition	Inform and alert the driver	Intermediate	Medium
	Lane departure warning	Prevent lane departure crashes	High	Medium
	Left-turn assist	Prevent potential conflict	High	Medium
	Pedestrian collision warning	Prevent pedestrian collision	High	Medium
	Rear cross traffic alert	Prevent backing collision	High	Medium
Level 1	Electronic stability control	Prevent rollover	High	High
	Adaptive cruise control	Prevent rear-end collision	High	High
	Cooperative adaptive cruise control	Prevent rear-end collision	Low	Medium
	Parental control	Prevent speeding	Intermediate	Medium
	Automatic emergency braking	Prevent rear-end collision	High	Medium
	Lane keeping	Prevent lane departure crashes	High	Medium
Level 2	Traffic jam ass	Driving assist	Low	Medium
	High speed automation	Driving assist	High	Medium
	Automated assistance in roadwork and congestion	Driving assist	High	Medium
Level 3	On-highway platooning	Driving assist, prevent rear end crashes	Intermediate	Medium
	Automated operation for military applications	Prevent human fatalities	Unknown	Low
Level 4/5	Self-driving vehicle	Replace human drivers	High	Low
	Emergency stopping assistant	Response when lose control human drivers	High	Low

Research Task 1: Literature Review

Concepts and Potential Benefits

- Connected and Automated Vehicle



As mentioned by Li and Kockelman (2016), CAVs may significantly reduce the number of crashes and save current **crash costs** in the U.S. by at least $126 billion per year.

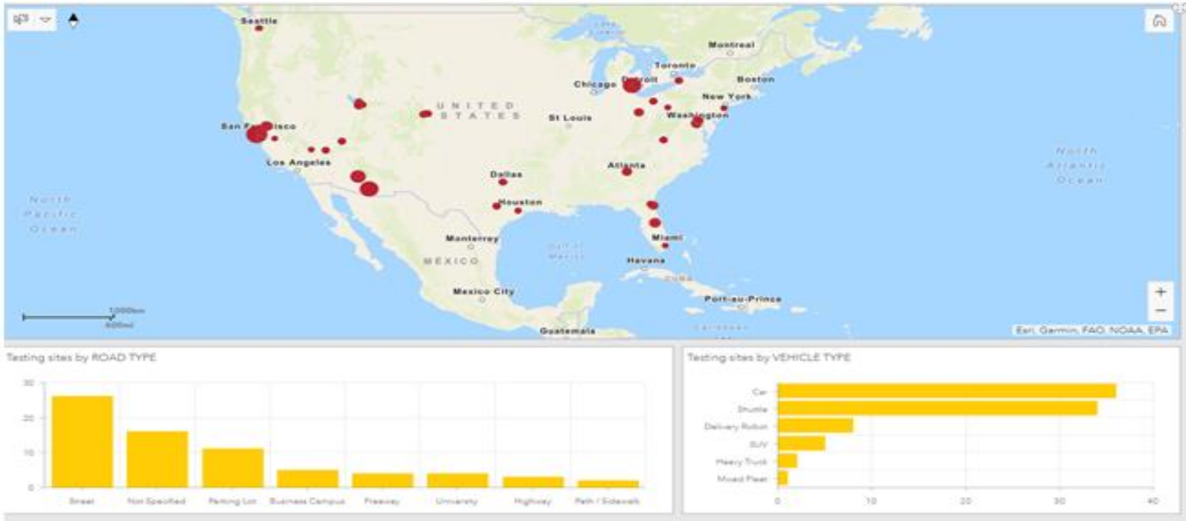
CAVs can also **increase mobility** by providing opportunities to people who cannot afford a vehicle, people who prefer not to drive, people with disabilities, and elder people who cannot drive safely (Duncan et al., 2015).

The communication and automation technologies also enable CAVs to drive **more smoothly** than human drivers, with **smaller following gaps and coordinated speeds**, and these will also **reduce vehicle emissions** by **reducing stop-and-go frequency**.

Research Task 1: Literature Review

Deployment of and Market Forecast for AVs

The testbed locations are generally isolated places or low population density areas of the city



AV TEST Initiative https://www.nhtsa.gov/automated-vehicles-safety/av-test-initiative-tracking-tool

Table 3 Volvo autonomous vehicle project

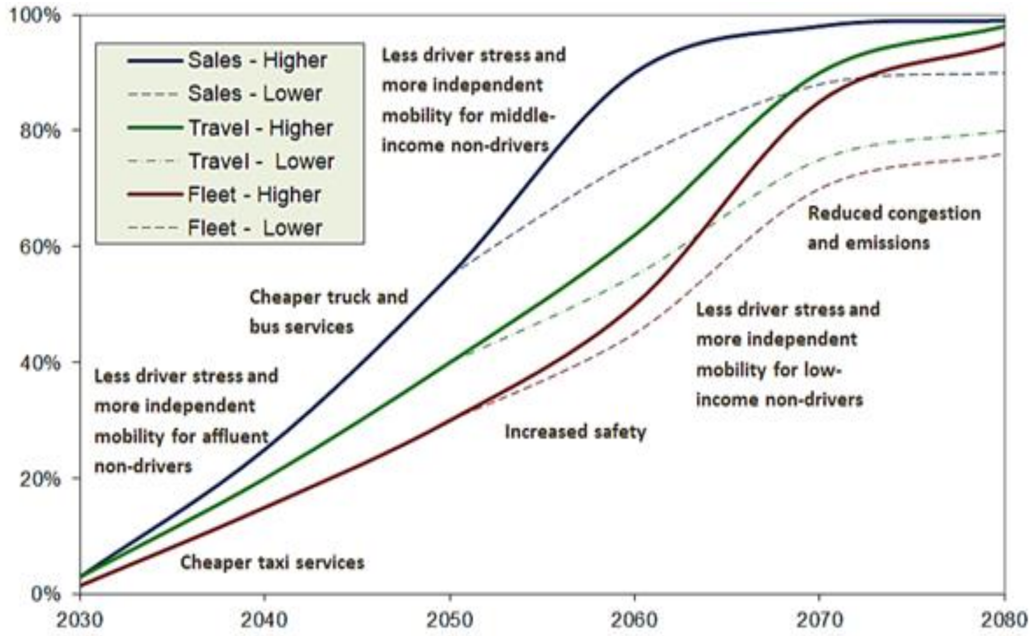
Start year	Autonomous technology project
2006	Collision warning with brake support
	Adaptive cruise control
	Lane departure warning
2007	Collision warning with auto brake
2008	City safety
2009	Safe Road Trains for The Environment (SARTRE) project begins
2010	Adaptive cruise control with queue assist
	Collision warning with full auto brake
	Pedestrian detection with full auto brake
2012	Traffic sign information
	Park assist pilot
	Cross-traffic alert
	Lane-keeping aid
	BLIS project (lane change assist)
	Cyclist detection with full auto brake
	Active high-beam control
	SARTRE project completed
2013	Concept of autonomous parking
	Drive Me project announced
2014	Pilot Assist
	Auto brake at intersection
2017	Drive Me pilot tested on real roads

Research Task 1: Literature Review

Deployment of and Market Forecast for AVs

- Market Forecast for Automated Vehicles

Litman (2020) provided a prediction that AVs' beneficial impacts on safety and congestion are likely to appear between 2050 and 2080. Litman (2020) also expected that human driving may be restricted after 2060 as the randomness of human driving behaviors might result in disruptive effects on the automation systems. **By 2050, with optimistic predictions, AVs are supposed to comprise 50% of all vehicle sales, 40% of all vehicle travel, and 30% of all vehicles. Meanwhile, the market penetration rates (MPRs) of the AVs are expected to be around 50% in 2060.**



Research Task 1: Literature Review

Traffic Flow Controls of CAVs

- Longitudinal Movement Control of CAVs
- Latitudinal Movement Control of CAVs

Table 4 Longitudinal movement control model for AVs and CAVs

Methodology	Vehicles	Reference paper
Intelligent Driver Model (IDM)	AV, HDV, CV	Kesting et al., 2007, 2008; Milanés and Shladover, 2014; Talebpour and Mahmassani, 2016; Treiber et al., 2000
IDM with constant-acceleration heuristic	AV, HDV	Kesting et al., 2010
Cooperative IDM	AV, CV, HDV	Zhou et al., 2017
MICroscopic Model for Simulation of Intelligent Cruise Control (MIXIC)	CV, CAV	Deng, 2016; Talebpour and Mahmassani, 2016; van Arem et al., 1997; Van Arem et al., 2006
Adaptive Cruise Control (ACC)	AV	Milanés and Shladover, 2014; Porfyri et al., 2018; Treiber et al., 2000
Cooperative Adaptive Cruise Control (CACC)	CAV	Shladover et al., 2012

Research Task 1: Literature Review

Intersection Capacity Analysis Methods

- Empirical Based Methods

Table 5 Summaries of Empirical-based Methods on Intersection

No.	Reference	Intersection Type	Method	Capability of the Method
1	HCM, 2010	Signal/unsignalized Intersection, Roundabout	Empirical calibrated equations	•Considering different roadway, geometric, traffic, and control conditions
2	Brilon and Wu, 2001	Unsignalized Intersection	Conflict-based technique	•Simplifying the theoretical structure compared to gap acceptance method
3	Dahl and Lee, 2012	Roundabout	Modified gap acceptance method	•Calculating the capacity more accuracy than unmodified model
4	Abhishek et al., 2019	Unsignalized Intersection	Modified gap acceptance model	•Incorporating driver impatience behavior with merging behavior; •Allowing different gap acceptance behaviors; •Facilitating the calculation of minor road capacity for an unsignalized intersection

Research Task 1: Literature Review

Intersection Capacity Analysis Methods

- Simulation Based Methods

Table 6 Summaries of Capacity Analysis Studies of CAVs under 100% Market Penetration Rate

No.	Reference	Aim and method	Criteria	Main result
1	Li et al., 2014	Optimize signal timing and trajectories	Throughput, Delay	Increase intersection **throughput by 2.7–20.2%** compared with actuated signal control
2	Abdelhameed et al., 2015	Minimize the travel time of CAVs while avoiding possible collisions	Throughput, Delay	Increase **throughput by 91%** compared to the fixed traffic light controller and the un-optimized fuzzy logic controller
3	Chen and Kang, 2016	Conflict-avoidance-based approach to coordinate CAVs	Delay	Reduce **trip delay by 31%-95%** compared with FCFS and signal control schemes
4	Liu et al., 2018	Assign priority and collision-free trajectories to CAVs	Throughput, Delay	Increase **throughput by 20%** compared to signal control scheme.
5	He et al., 2018	Conflict-avoidance-based approach to coordinate CAVs	Throughput, Travel time	Increase **throughput by 50%** compared to signal control scheme
6	Wei et al., 2018	Game theoretic framework to maximize throughput and minimize the accidents and congestion of the CAVs	Throughput	Increase the throughput by 140% and 43% in light and heavy traffic demand conditions, respectively
7	Sun et al., 2018	MCross scheme to maximize intersection capacity	Throughput	Almost double the intersection **capacity by 99.51%** compared to signal control scheme

Research Task 1: Literature Review

Intersection Capacity Analysis Methods

- Simulation Based Methods

Table 7 Summaries of Capacity Analysis Studies of CAVs under Mixed Traffic Environment

No.	Reference	Veh.	Object and method	Software	Criteria	Main result
1	Shladover et al. 2012	HDV, CV, AV, CAV	Simulation ACC and CACC based on field experiment data (for time gap settings) to estimate the effect on roadway capacity	AIMSUN	Capacity	•**40% market penetration rate** (MPR) of CACC equipped vehicles is a critical threshold to achieve a **10% improvement of the capacity**. •**100% MPR of CACC equipped vehicles** could **double the capacity**
2	Lee and Park, 2012	CV	Cooperative Vehicle Intersection Control	VISSIM	Through-put, Delay, Emission	•The **throughput** and total travel time were **improved by 8%** and 33% compared to actuated signal control system
3	Jiang et al., 2017	CAV	Optimizing speed of CAVs	VISSIM, Matlab	Fuel, CO2, Through-put	•Benefits grow with the MPRs of CAVs until they **level off at about 40% MPR**.
4	Sharon and Stone, 2017	CAV	Hybrid autonomous intersection management	SUMO	Queue length, Through-put	•H-AIM can decrease delays for AVs even **at a 1% MPR.** •With **50% MPR of CAVs**, increase the **throughput** for four-way intersection and three-way intersection by **10% and 6%**, respectively.
5	Algomaiah and Li, 2019	CAV	A first-come-first-serve reservation at intersection	VISSIM	Through-put, delay	•The proposed control system outperforms traffic signals **after a 75% MPR of CAVs**.

Research Task 1: Literature Review

Intersection Capacity Analysis Methods

- Simulation Based Methods

Table 8 Summaries of Other Performance Measures of CAVs under Mixed Traffic Environment

No.	Reference	Veh.	Object and method	Software	Criteria	Main result
1	Lee et al., 2013	CV	Cumulative travel-time responsive (CTR) real-time intersection control	VISSIM, Matlab	Delay, speed	•The CTR algorithm improves the system performance after a 30% MPR of CVs. •CTR algorithm outperformed the actuated controls after a 70% MPR of CVs.
2	Guler et al., 2014	CV	Optimizing the departure sequences	Matlab	Delay	•CVs with MPRS from 0% up to 60% can significantly reduce the average delay. •The average delay could be significantly reduced even with low MPRs (20–40%).
3	Yang et al., 2016	CV, AV	Optimization of departure sequence and trajectory by maximize the speed entering the intersection	Java	Stops, Delay	•This algorithm performs better than the actuated signal control after a 50% MPR of CVs. •Even a 50% information level for CVs could significantly decrease the delay and stops.
4	Yang et al., 2017	CAV	Eco-CACC system that computes the fuel-optimum vehicle trajectory	Integratio n	Fuel	•Eco-CACC system produces vehicle fuel savings up to 40% at a 100% MPR of CAVs. •Lower MPRs of CAVs increase fuel consumption on multi-lane roads, and the system decreases the fuel consumption only after a 30% MPR of CAVs.
5	Du et al., 2017	CV	Coordinate CVs at adjacent signalized intersections.	–	Fuel	•Increase the MPRs of CVs would decrease fuel consumption. •Fuel consumption will increase if the CV is following an HDV.
6	Pourmehrab et al., 2018	AV	Headway minimization	Matlab	Travel Time	•The average travel time decreases with higher MPRs of AVs.
7	Zhao et al., 2018	AV	Minimize the fuel consumption for platoons	Matlab	Fuel, Travel time	•Both fuel consumption and travel time decrease with the increasing MPRs of AVs. •The benefits of cooperation between AVs and HDVs are most evident for lower MPRs, and a platoon size of 5 can reduce 22% fuel consumption under a 60% MPR of AVs.
8	Liang et al., 2019	CV, AV, SGV	Jointly optimizing the signal phase and timing plan along with speed guidance	Java	Delay, stops	•The average delay and number of stops decrease with higher MPRs of CV, AVs, and SGVs (HDV with speed guidance-enabled vehicles). •The marginal benefits decrease rapidly when MPRs of the CVs exceed 40%.
9	Virdi et al., 2019	CAV	Safety assessment of mixed flow	VISSIM	Conflicts	•CAVs at low penetration rates increase conflicts at signalized intersections while decrease conflicts at priority-controlled intersections.

Research Task 1: Literature Review

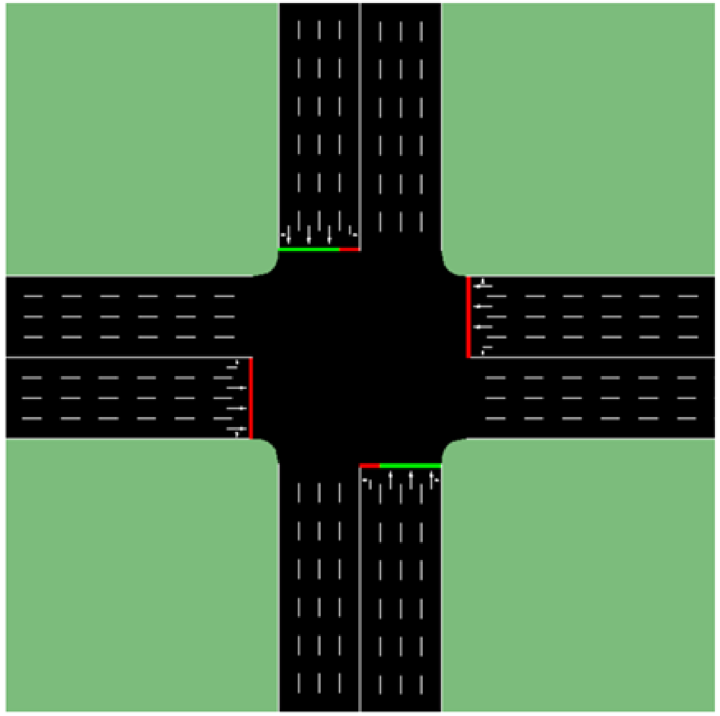
Intersection Modeling Scenarios and Parameters

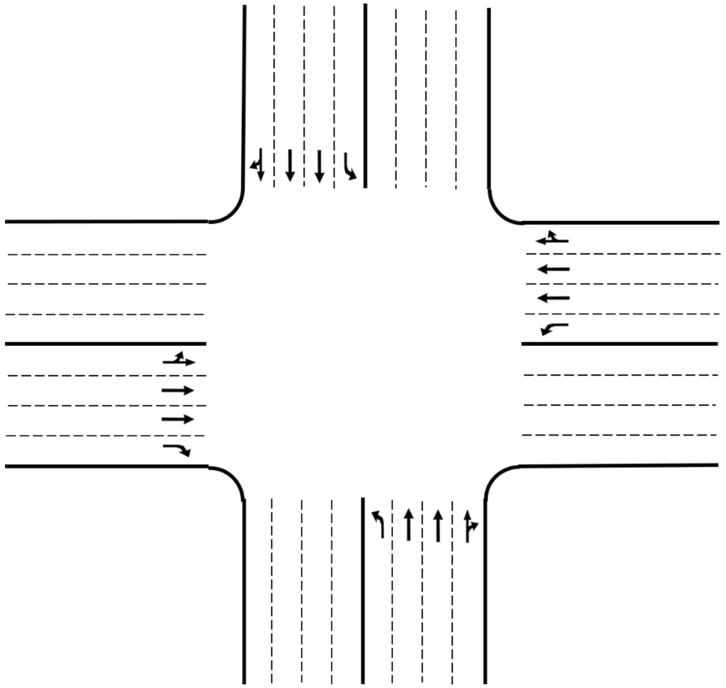
Table 9 Summary of Intersection Modeling Scenarios with CAVs

No.	Reference	Intersection Type	Scenarios	Findings
1	Jiang et al., 2017	Single lane signalized intersection	Mixed flow; Traffic demands: non-saturated (v/c = 0.5), saturated (v/c = 1), oversaturated (v/c = 1.2)	•Increase the throughput by 7.06% and 10.80% with 60% MPR of CAVs under saturated (v/c = 1) and oversaturated (v/c = 1.2) conditions, respectively
2	Sharon and Stone, 2017	A four-way intersection and a three-way intersection	Mixed flow; Traffic demands from low to high (150 - 750 vehicles/hour/lane)	•With 50% MPR of CAVs, the H-AIM can increase the throughput for four-way intersection and three-way intersection by 10% and 6%, respectively.
3	Yang et al., 2017	Single lane and multilane signalized intersections	Mixed flow	•Increase the fuel consumption if the MPR of eco-CACC vehicles are over 30%
4	Sun et al., 2018	An intersection with continuous flow design and tandem control	Unbalanced flow, heavy left-turn traffic, heavy conflicting movements, all demands flow cases	•Increase intersection capacity by 99.51% compared to signal control
5	He et al., 2018	Unsignalized intersection with all-direction turn lanes	Increase traffic demands from 100 – 1000 (vehicles/hour/lane)	•Increase 50% of the throughput compared to signal control scheme
6	Algomaiah and Li, 2019	Next-generation interchange with different combinations of dedicated and shared lanes	Mixed flow; Communication range (600, 800, 1000 ft); Traffic demands from 400 to 1000 vehicles/hour/lane	•Increase about 50% of the throughput with 100% MPR of CAVs compared to signal control scheme; •800 ft communication range shows a relatively lower delay

Basic intersections for Simulation

A typical four-leg intersection will be used for basic simulation testing scenario





Candidate intersections for case study

A signalized intersection in the city of Charlotte, NC

N Tryon St. & W. T. Harris Blvd.

Traffic period covers 1 h of the midday peak, from 12:30 p.m. to 1:30 p.m. on April 3rd, 2018

Table 1. Traffic flow throughout the study period.

Leg direction	N. Tryon St Southbound			N. Tryon St Northbound			Harris Blvd Westbound			Harris Blvd Eastbound		
Volume	R	T	L	R	T	L	R	T	L	R	T	L
	216	293	353	251	397	404	239	1229	257	169	1050	168

Research Task 2: Identify Potential Intersections

Candidate intersections for case study

Two adjacent signalized intersections in the City of Greensboro, NC (near NCA&T campus)

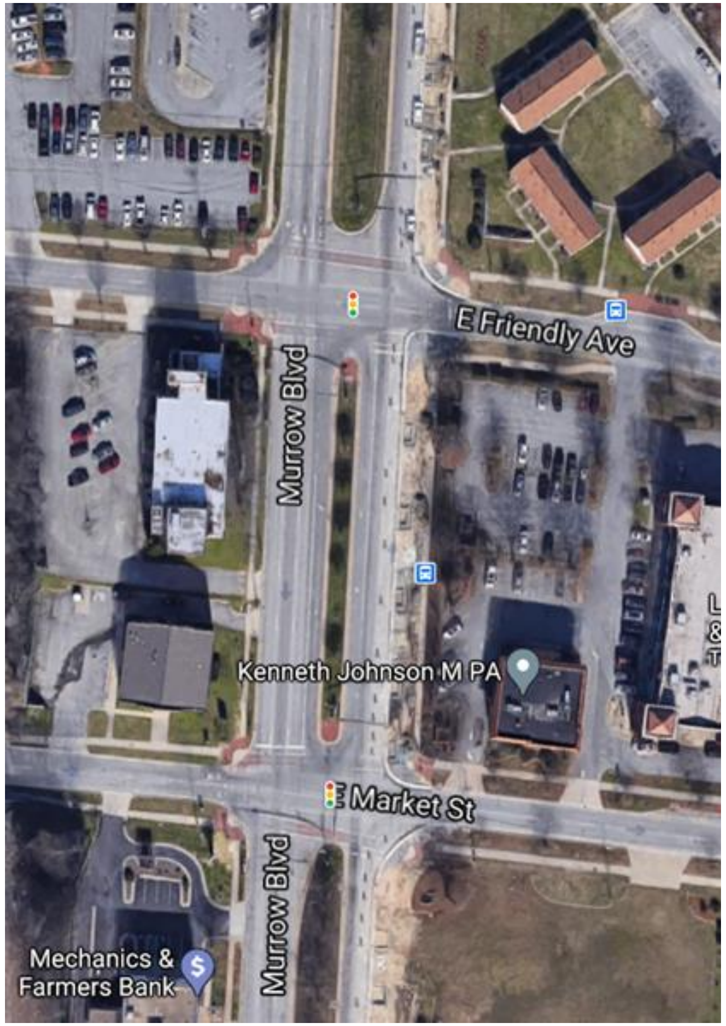
Market St. & Murrow Blvd.

Friendly Ave. & Murrow Blvd.

1 h of the afternoon peak, from 4:45 p.m. to 5:45 p.m. on Feb 7th, 2018.

Table 2-2. Signal schemes during the afternoon peak hours

PM Peak	Param	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8	Cycle Time	Offset Time	Split Number	Seq Number
Friendly @ Murrow	Time	0	35	23	32	0	35	0	55	90	6	22	9
Market @ Murrow	Time	0	38	22	30	0	38	0	52	90	81	22	9



Research Task 2: Identify Potential Intersections

Candidate intersections for case study

A signalized intersection in the City of Greensboro, NC (near NCA&T campus)

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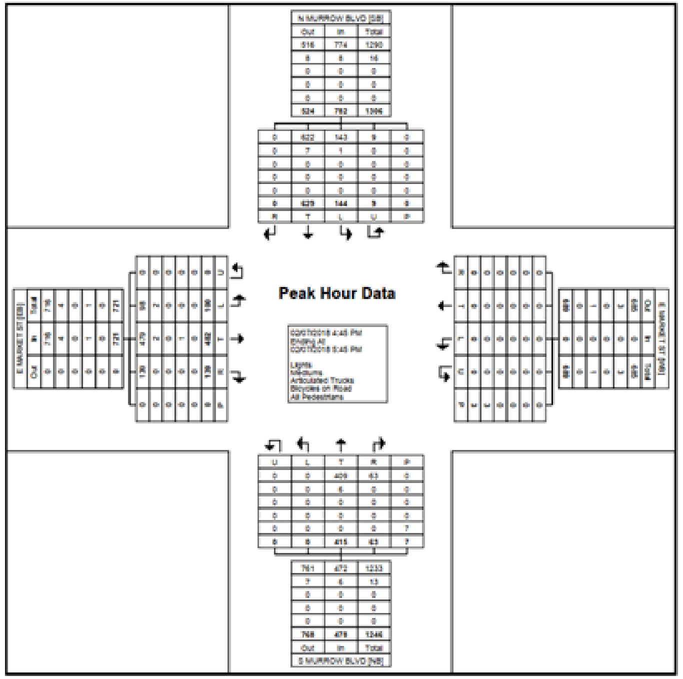
1 h of the afternoon peak, from 4:45 p.m. to 5:45 p.m. on Feb 7th, 2018.



Turning Movement Peak Hour Data Plot (4:45 PM)

Candidate intersections for case study

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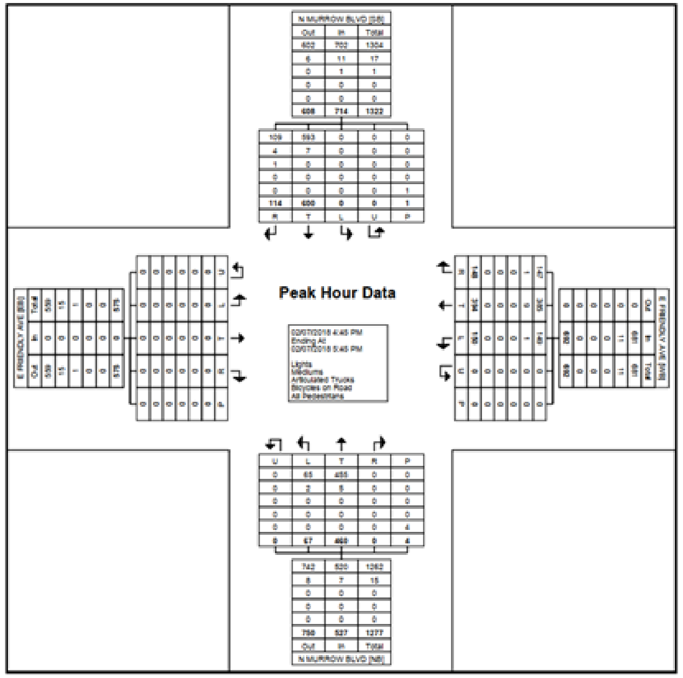
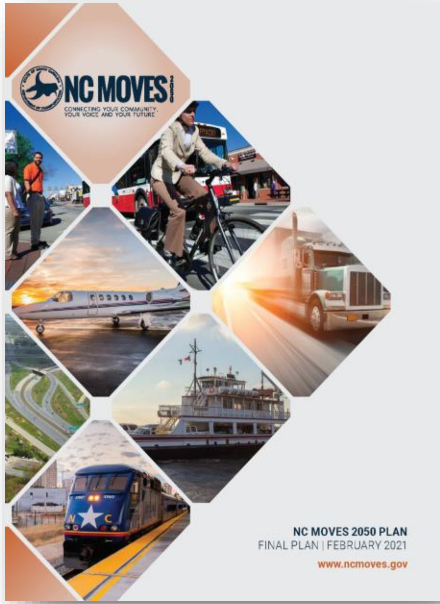


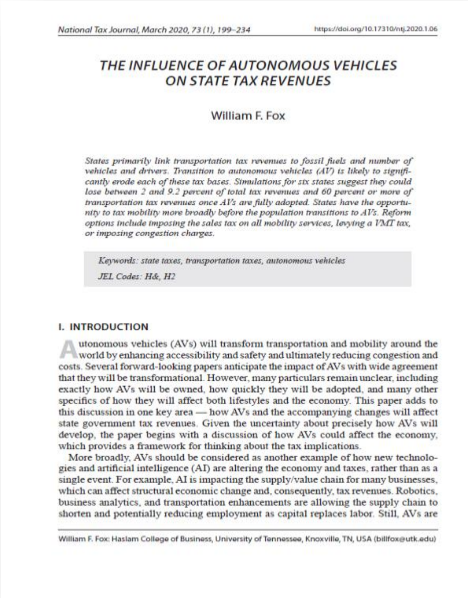
Turning Movement Peak Hour Data Plot (4:45 PM)

CAV Revenue Impacts – Scope Snapshot

Literature Review & CAV Revenue Analysis

- Reviewed 50+ journal articles, reports, news articles, and online documentation
- Key Sources: NC F1RST Commission Report | NC Moves 2050
- Literature and data extract to inform revenue analysis





National Tax Journal, March 2020, 73 (1), 199–234 https://doi.org/10.17310/ntj.2020.1.06

THE INFLUENCE OF AUTONOMOUS VEHICLES ON STATE TAX REVENUES

William F. Fox

States primarily link transportation tax revenues to fossil fuels and number of vehicles and drivers. Transition to autonomous vehicles (AV) is likely to significantly erode each of these tax bases. Simulations for six states suggest they could lose between 2 and 9.2 percent of total tax revenues and 60 percent or more of transportation tax revenues once AVs are fully adopted. States have the opportunity to tax mobility more broadly before the population transitions to AVs. Reform options include imposing the sales tax on all mobility services, levying a VMT tax, or imposing congestion charges.

Keywords: state taxes, transportation taxes, autonomous vehicles

JEL Codes: H&, H2

I. INTRODUCTION

Autonomous vehicles (AVs) will transform transportation and mobility around the world by enhancing accessibility and safety and ultimately reducing congestion and costs. Several forward-looking papers anticipate the impact of AVs with wide agreement that they will be transformational. However, many particulars remain unclear, including exactly how AVs will be owned, how quickly they will be adopted, and many other specifics of how they will affect both lifestyles and the economy. This paper adds to this discussion in one key area — how AVs and the accompanying changes will affect state government tax revenues. Given the uncertainty about precisely how AVs will develop, the paper begins with a discussion of how AVs could affect the economy, which provides a framework for thinking about the tax implications.

More broadly, AVs should be considered as another example of how new technologies and artificial intelligence (AI) are altering the economy and taxes, rather than as a single event. For example, AI is impacting the supply/value chain for many businesses, which can affect structural economic change and, consequently, tax revenues. Robotics, business analytics, and transportation enhancements are allowing the supply chain to shorten and potentially reducing employment as capital replaces labor. Still, AVs are

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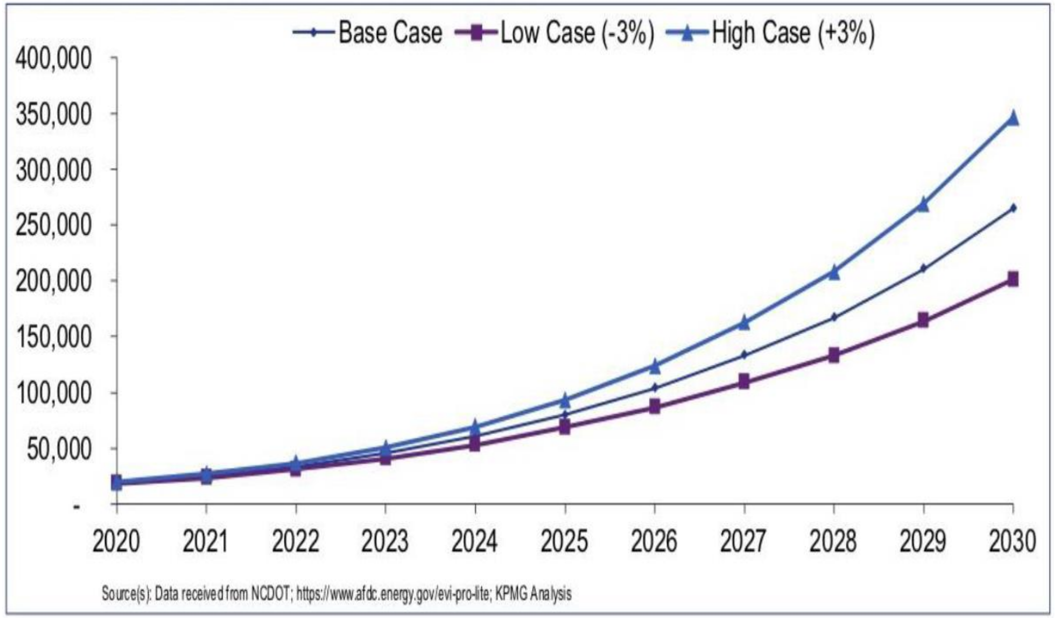
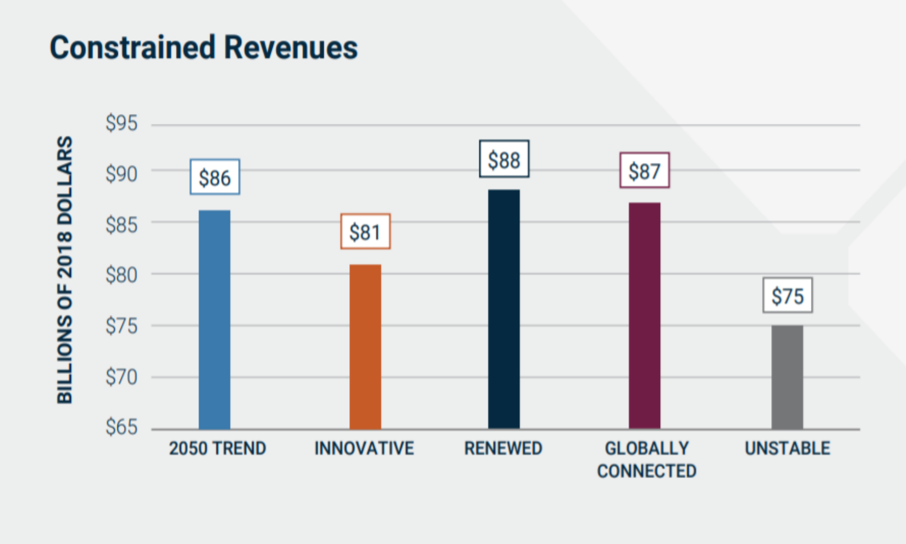
North Carolina Electric Vehicle Forecast

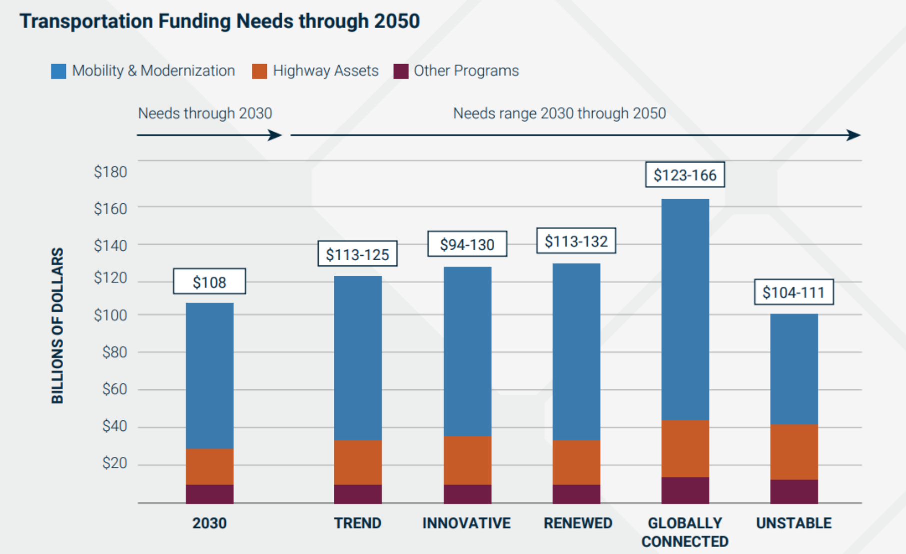


NC F1RST Commission Findings, 2021.

- Base: 2020: 25,000 | 2025: 80,000 | 2030: 260,000
- Low: (-3%): 2020: 25,000 | 2025: 65,000| 2030: 200,000
- High: (+3%): 2020: 25,000 | 2025: 95,000 | 2030: 350,000

Literature Review Update





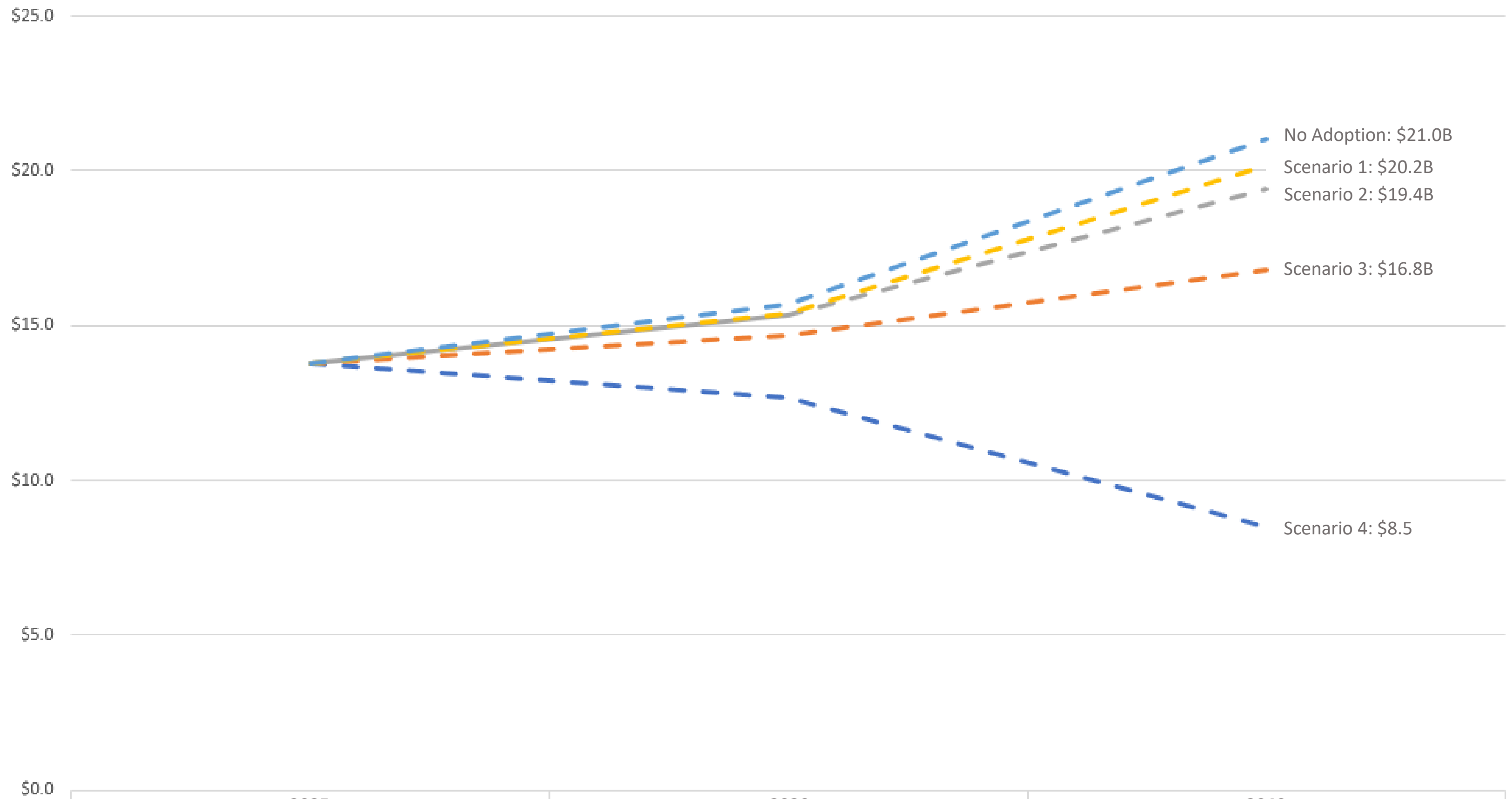
NC Moves 2050 Plan

- $75 billion to $88 billion in revenue by 2050
- $94 billion to $166 billion in transportation needs
- Use this report to build model CAV model bounds

NC Moves 2050 Plan, 2021.

Literature Review Update

Texas Transportation Funding Projections Subject to Four CAV Adoption Scenarios



	2025	2030	2040
S4	$13.8	$12.7	$8.5
S3	$13.8	$14.7	$16.8
S2	$13.8	$15.3	$19.4
S1	$13.8	$15.4	$20.2
No CAVs	$13.8	$15.7	$21.0

Revenue Change from 2025-2040

- No CAV Adoption: $21 billion
- S.1: 0% vehicle reduction; phase in CAVs over 30 years (**4.0%** loss in revenue)
- S.2: 40% vehicle reduction; phase in CAVs over 50 years (**7.6%** loss in revenue)
- S.3: 40% vehicle reduction; phase CAVs over 30 years (**20.1%** loss in revenue)
- S.4: 50% vehicle reduction; phase in CAVs over 15 years (**59.5%** loss in revenue)

Source: ITRE Analysis using Fox (2020) data

Literature Review Findings

In the 25 largest U.S. cities, nearly $5 billion in revenue collected from:

- Parking-related activities
- Camera and traffic citations
- Gas taxes
- Towing
- Vehicle registration and licensing fees

Equates to $129 per capita for these 25 jurisdictions

These revenue mechanisms will be important variables in our revenue model

Motor Fuels Tax

Enforced Parking Fees

Traffic Violation Fees

Vehicle Impound Fees

Vehicle Registration Fees

Next Steps

Progress Update:

- Completed the literature review
- Assembling assumptions, guideposts, and data obtained from the Lit to build revenue model
- Assessing the revenue impacts and opportunities of automated, connected, electric, and shared vehicles.

Center Admin Activities		FY 2020												FY 2021												FY 2022											
Task	Description	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan
1	Literature Review																																				
2	Identify Potential Intersections																																				
3	Design Scenarios for the Conduct of Simulation																																				
4	Use Simulations to Examine the Established Modeling Framework																																				
5	Develop Guideline on the Intersection Capacity Adjustments Considering Different Level of CAV Penetration																																				
6	Conduct a Revenue Impact Analysis and Propose New Methods																																				
7	Document Research Findings and Develop a Final Report																																				
8	Project Management Activities																																				

NC Transportation Center of Excellence on Connected and Autonomous Vehicle Technology (NC-CAV)

Project 2
Assessing North Carolina Readiness for CAVs in Traditional and Emerging Infrastructure Needs

Principal Investigator:
Thomas Chase (NCSU-ITRE) Email: rtchase@ncsu.edu

Other Investigators:
Shih-Chun Lin (NCSU) Email:slin23@ncsu.edu
John Kelly (NCAT) Email: jck@ncat.edu
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Research Thrust 2: CAV Infrastructure

Project 2: Assessing North Carolina Readiness for CAVs in Traditional and Emerging Infrastructure Needs

Principal Investigator: T. Chase (ITRE)

Other Investigators: NCSU: S. Lin; NCA&T: J. Kelly, A. Eroglu

Scope: Thrust 2 researchers will analyze the readiness of the existing transportation infrastructure and maintenance programs to support CAV deployment and will investigate the emerging infrastructure required for the adoption of future CAV technologies.

Objectives:

- Document NCDOT Infrastructure Programs Impacted by CAV Needs
- Develop and test a 5G architecture for secure V2I applications
- Recommend Program Enhancements to Advance NC CAV Infrastructure Readiness

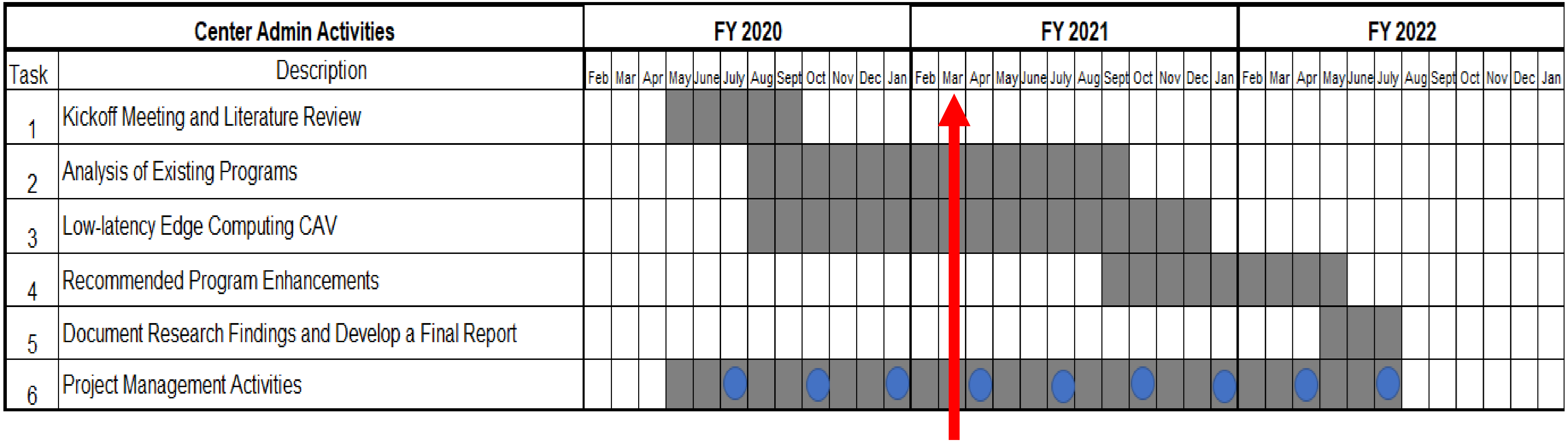
Research Background

North Carolina is preparing for Connected and Autonomous Vehicles (CAVs) through multiple initiatives:

- NCDOT-sponsored report “NC Readiness for Connected and Autonomous Vehicles (CAV)”
- Highly Automated Vehicle Committee appointed by the State Legislature
- Connected Automated Shuttle Supporting Innovation (CASSI)
- Multiple ongoing CAV Research Projects

Safe CAV deployment will require significant investment in both traditional and emerging infrastructure.

Project 2: Research Tasks and Timeline



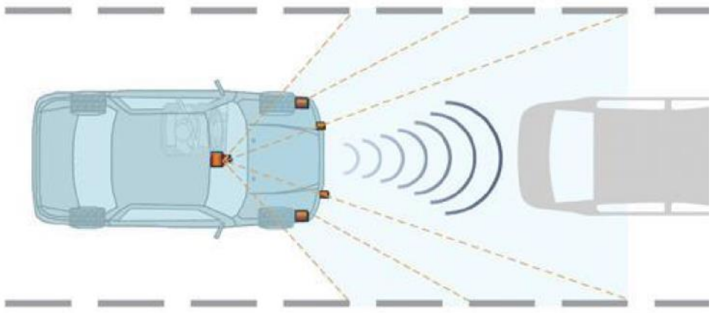
Research Task 1: Literature Review

CAV Impacts on Highway Geometry

- Highway geometric refers to the physical design of a roadway
  - Radii of horizontal curves
  - The rates of vertical slope changes for connecting roadway segments with different grades
  - Lengths of acceleration and deceleration lanes
- Highway geometry design considerations
  - Design Vehicle
    - Physical features such as geometrical dimensions
    - Mechanical performance
  - Design Driver
    - Knowledge of the system (result of previous experience and training)
    - Skills and attitudes (ability to act upon attained information and/or prior knowledge)
    - Physiological characteristics (e.g., hearing, seeing)

Design Vehicle and Design Driver

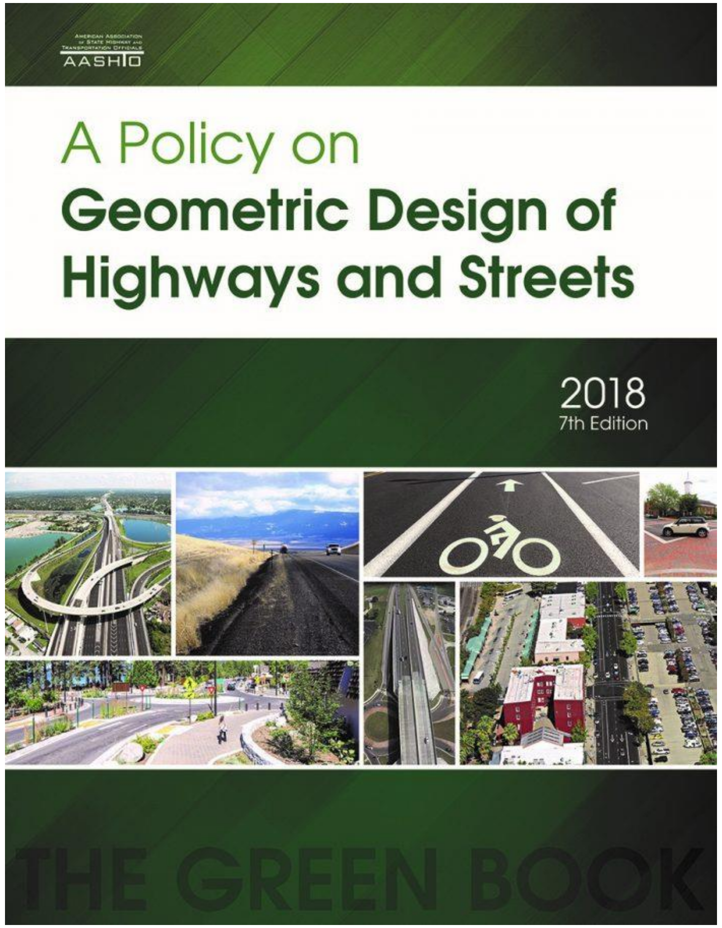
- Design driver and vehicle have evolved and will continue to evolve
  - Highway standards were initially developed from research in the 1930s and 1940s with young drivers, low speeds, and vehicles of that era.
  - Highways are now designed for the older drivers, speeds up to 85 mph, and modern vehicles.
- How will CAVs change design driver/vehicle?
  - Advanced sensors
  - Wireless communications to provide timely situation awareness



Research Task 1: Literature Review

Current Geometry Design Controlling Criteria

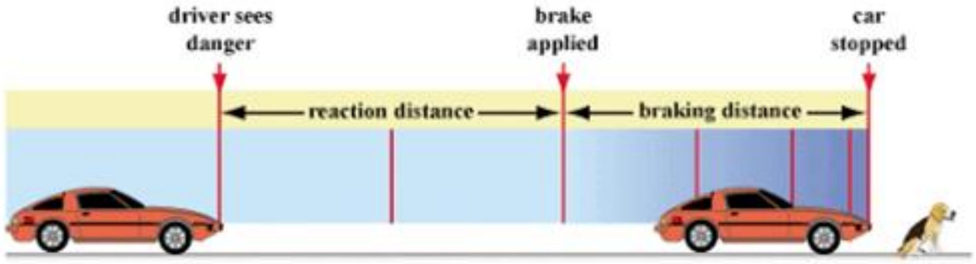
- Design Speed
- Lane Width
- Shoulder Width
- Horizontal Curve Radius
- Superelevation Rate
- Maximum Grade
- Stopping Sight Distance
- Cross Slope
- Vertical Clearance
- Design Loading Structural Capacity



Research Task 1: Literature Review

How Will SSD Impact Geometrics?

"… the sight distance at <u>every point</u> along a roadway should be at least that needed for a <u>below-average</u> driver or vehicle to stop."



$$SSD = 1.47\ Vt + 1.075\ \frac{V^2}{a}$$

SSD = stopping sight distance, ft
V = design speed, mph
t = brake reaction time, **2.5s**
a = deceleration rate, ft/s^2

- Roadway
  - Crest curves
  - Sag curves
  - Horizontal curve radius
- Intersection Sight Distance
- Objects Offset Along Road
  - Median Barriers
  - Crash Walls
  - Parapets
  - Bridge Abutments

How Will CAVs Impact SSD?

- Perception-Reaction Time (PRT)
  - AASHTO recommends 2.5 seconds as PRT
  - PRT increases with
    - Age
    - Fatigue
    - Complexity of the task
    - Physical impairments
    - Presence of alcohol and drugs
  - What happens if CAVs decrease PRT to 1 sec? to 0.5 sec?

- Maximum Deceleration
  - What happens if CAVs increase deceleration rate from 11.2 ft/s^2 to 14.8 ft/s^2?

How Will CAVs Impact SSD?

- SSD on Level Roadway under various Conditions

Design Speed (mph)	Max Deceleration = 11.2 ft/s^2						Max Deceleration = 14.8 ft/s^2	
	PRT (s)	SSD (ft.)	PRT (s)	SSD (ft.)	PRT (s)	SSD (ft.)	PRT (s)	SSD (ft.)
40	2.5	300	1	210	0.5	185	0.5	145
50	2.5	425	1	315	0.5	275	0.5	220
60	2.5	565	1	435	0.5	390	0.5	305
70	2.5	730	1	575	0.5	520	0.5	410

CAV Impacts on Highway Infrastructure

Highway Infrastructure Categories			
Physical Infrastructure	**Traffic Control Devices**	**TSMO and ITS Infrastructure**	**Multimodal Infrastructure**
Pavements, Bridges and Culverts	Pavement Markings, Traffic Signs, Traffic Signals, Temporary Traffic Control, Roadside Hardware	ITS Roadside Equipment, TSMO Strategies, TSMO Systems	Bicycle, Pedestrian, and Transit Infrastructure, Curb Space

Source: FHWA, 2020

Research Task 1: Literature Review

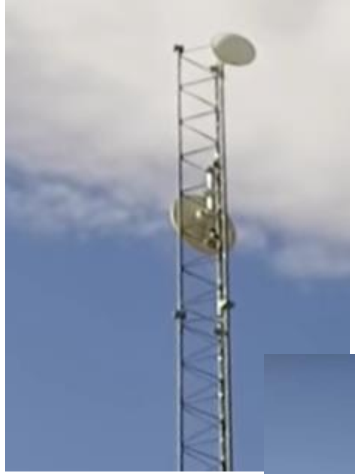
CAV Impacts on Highway Infrastructure

- Physical Infrastructure - Pavements
  - Lowered threshold for pavement distresses (i.e., potholes, edge wear) for AVs.
  - Increased pavement rutting potential (i.e., decreased wheel wander, increased lane capacity).
  - Increased potential for faster accumulation of pavement damage.
- Physical Infrastructure - Bridges
  - Heavy vehicles platooning with small headways and little lateral offset may increase dynamic loads

Research Task 1: Literature Review

CAVs Rely on RSUs

- *“Information exchange must address connectivity between the vehicles and the roadside infrastructure. Without the digital infrastructure and data, ADS operability that is reliant on information from roadside equipment would essentially become non-functional”*



- RSU Deployment Considerations
  - RSU and OBU systems should follow a national standard and the systems must be interoperable with the devices on all vehicles.
  - The messages sent and received through Cellular V2X should be uniform in all States in the U.S.
  - The deployment of RSUs should take into account the roadway and traffic features of the sparse, rural areas in the U.S.

Research Task 1: Literature Review

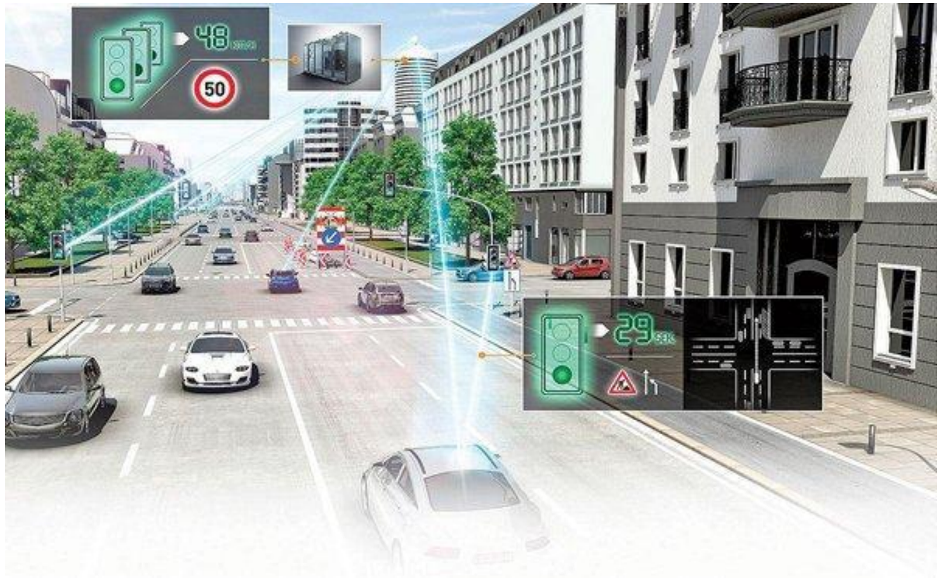
Infrastructure Needs Evaluation for Different Vehicle Technologies

#	Vehicle Technology	Infrastructure Need	Infrastructure Cost	#	Vehicle Technology	Infrastructure Need	Infrastructure Cost
1	**Forward Collision Warning**	None	None	**11**	**Lane Departure Warning**	Lane marks	Low
2	**Blind Spot Monitoring**	None	None	**12**	**Left Turn Assist**	Lane marks	Low
3	**Adaptive Headlight**	None	None	**13**	**Lane Keeping**	Lane marks	Low
4	**Automatic Emergency Braking**	None	None	**14**	**Traffic Jam Assist**	Lane marks	Low
5	**Electric Stability Control**	None	None	**15**	**Traffic Sign Recognition**	Traffic sign	Moderate
6	**Parental Control**	None	None	**16**	**High Speed Automation**	Lane marks, Traffic sign	Moderate
7	**Emergency Stopping Assistance**	None	None	**17**	**On-Highway Platooning**	Lane marks, Traffic sign	Moderate
8	**Automated Operation for Military**	None	None	**18**	**Automated Assistance in Roadwork and Congestion**	Lane marks, Beacons, Guide walls	High
9	**Adaptive Cruise Control**	None, possible dedicated lane	None/Depends	**19**	**Auto-Valet Parking**	Parking facilities	High
10	**Cooperative Adaptive Cruise Control**	None, possible dedicated lane	None/Depends	**20**	**Driverless Car**	Lane marks, Traffic sign, Lighting	High

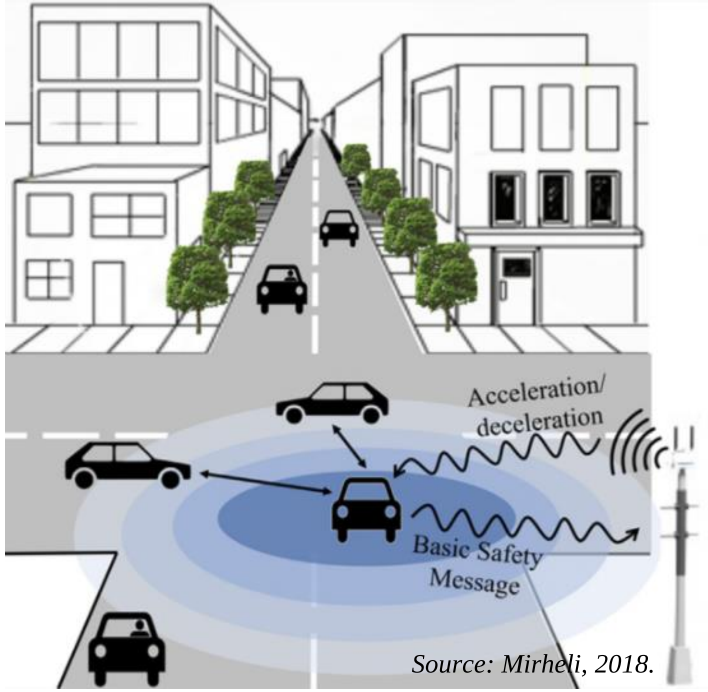
Adapted from Kockelman et al., 2017)

Traffic Control Devices

- Connected Signals
  - I2V wireless communications allows for the signal controller directly sending signal timing information to the connected vehicles



- Signal-free Intersection
  - Is there any needs of physical signal heads at intersections in a fully automated future?



Source: Mirheli, 2018.

Research Task 1: Literature Review

Pavement Markings

- Generally, human vision needs more retroreflectivity than machine vision systems
- Number of image pixels for machine vision detection is critical, especially important under challenging conditions (recommend increase to 6-inch wide markings)
- Daytime appearance is just as important as nighttime
- Daytime contrast on light colored pavements is particularly helpful

Width of Longitudinal Markings

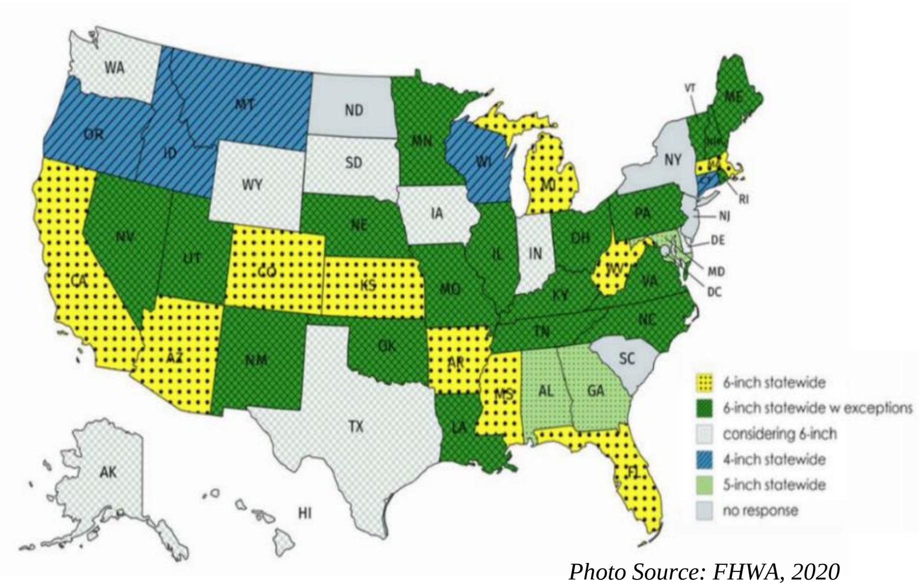


Photo Source: FHWA, 2020

Research Task 1: Literature Review

Signage

- Optical cameras and machine vision systems have limited resolution and range vs. some human drivers – will be confused by damaged, faded, or noncompliant signs
- Standardization of traffic signs, in terms of content design and mounting location, can improve reliability of detection by reducing complexity of machine vision processing
- Digital signing may be challenging for in-vehicle camera systems (but might not be a problem for CAVs)

Photo Source: FHWA

Research Task 2: Existing Programs

Analysis of Existing Programs

NCDOT Infrastructure:

- Construction and Capital Investment
- Standards and Policies
- Asset Management
- Maintenance
- ITS
- Roadway Design, Signing and Delineation, Integrated Mobility, etc.

Commercial Cellular and Fiber Networks

Research Task 2: Existing Programs

Analysis of Existing Programs

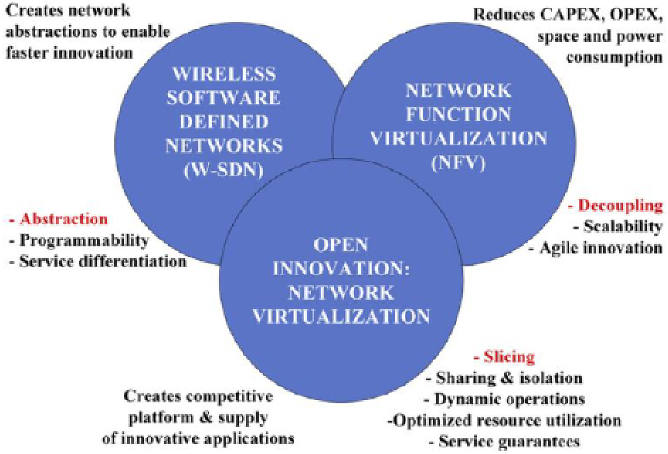
Next Steps: NCDOT Survey and Select Interviews

Research Task 3: Computing CAV

Next-Generation Wireless Networking Architecture

From Softwarization to Intelligence

PHASE I: Bring software-defined infrastructure into wireless



I. F. Akyildiz, **S.-C. Lin**, and P. Wang, "Wireless Software-Defined Networks (W-SDNs) and Network Function Virtualization (NFV) for 5G Cellular Systems: An Overview and Qualitative Evaluation," *Computer Networks (Elsevier) Journal*, vol. 93, part 1, pp. 66-79, December 2015.

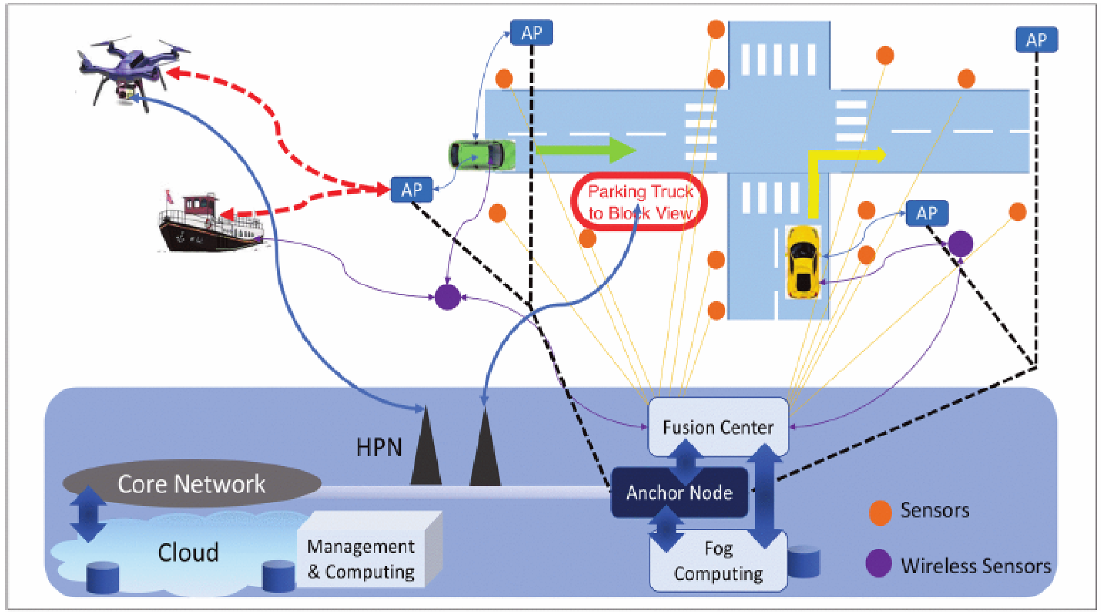
PHASE II: Incorporate AI/ML/DL into wireless: **Computation-based wireless edge networks**

S.-C. Lin, K.-C. Chen, and A. Karimoddini, "SD-VEC: Software-Defined Vehicular Edge Computing with Ultra-Low Latency," under review, 2020.

K.-C. Chen, **S.-C. Lin**, C.-H. Liu, A. Molisch, and G. Fettweis, "Wireless Networked Multirobot Systems in Smart Factories," *Proceedings of the IEEE*, 2020.

Research Task 3: Computing CAV

SD-VEC: Software-Defined Vehicular Edge Computing



S.-C. Lin, K.-C. Chen, and A. Karimoddini, “SD-VEC: Software-Defined Vehicular Edge Computing with Ultra-Low Latency,” under review, 2020.

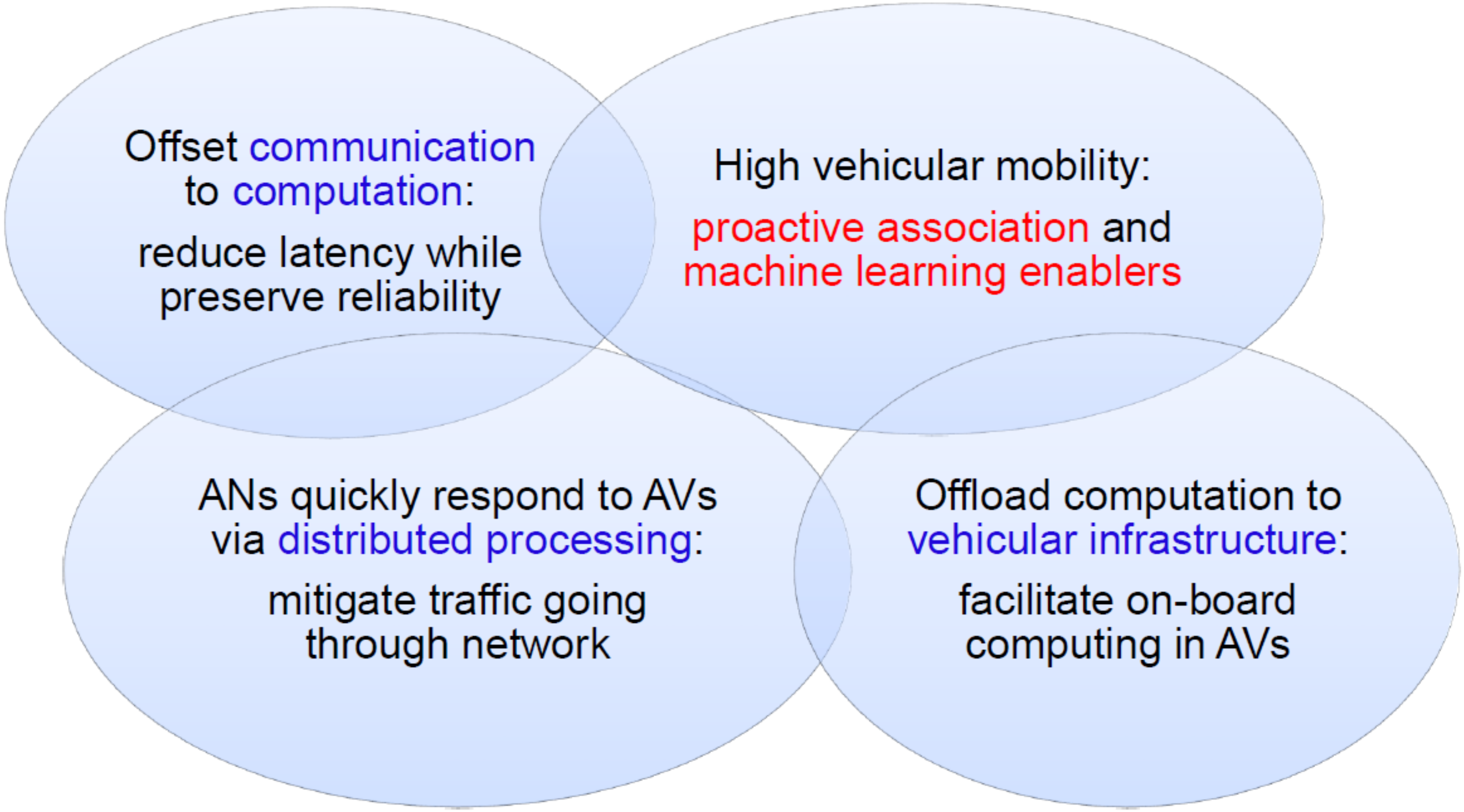
Heterogeneous Network Architecture & Multi-Scale Computing Environment

Distributed computing architecture for autonomous vehicles (AVs)

- Extend the network abstraction and provides an interface to allow intelligent anchor node (ANs) control both data delivery and processing
- ANs can explore a set of computing operations while establishing the minimum one-time signaling between AVs and the infrastructure (access points)

Research Task 3: Computing CAV

Advantages of SD-VEC



Research Task 3: Computing CAV

Computing-Based Vehicular Networking Infrastructure

Ultra-fast vehicular data plane with high reliability

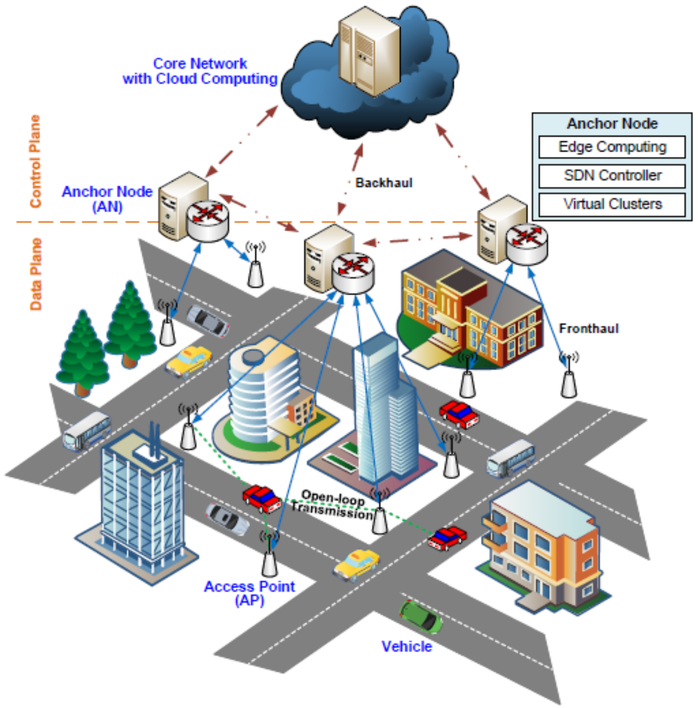
- Exploit latency-minimum open-loop transmissions
- Introduce smart frontend and real-time beamformers
- Extend multiuser detection for grant-free access

Vehicle-centric virtual cells

- Provide multi-path-based error control
- Distributed transmit point at ANs: cooperative gain

Required computing operations:

- Proactive Open-Loop Access & Wireless Learning
- Virtual Clusters and Error Control Mechanisms
- Machine Learning-Enhanced Mobility Management



System architecture of SD-VEC

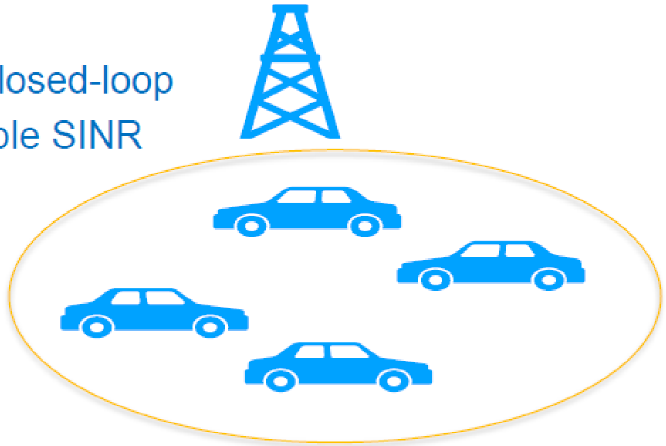
Research Task 3: Computing CAV

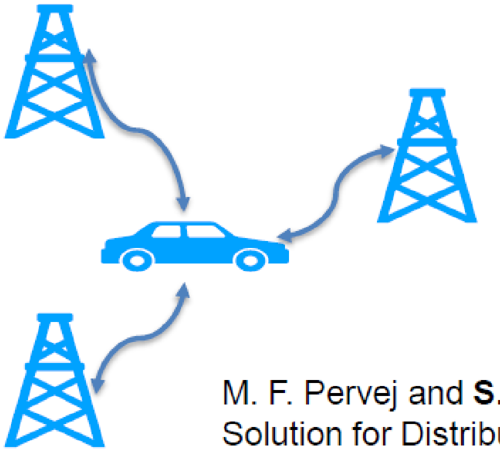
Proactive Open-Loop Vehicular Data Plane

Conventional protocol-based solution:

- A cell uses one base station to serve multiple vehicles

Complex handover of closed-loop
Cell-edge effect: terrible SINR





M. F. Pervej and **S.-C. Lin**, "Multi-Agent Learning Solution for Distributed V2V Communication Using Grant-Free Random Access," under review, 2020.

Our solution: No re-transmission! Grant-free! No scheduling!

- A single vehicle: as the center node of a virtual AP cluster
- Discard handoff/handover, but consider proactive network association **(just connect to APs)**
- Multiple APs serve this vehicle via cooperative communications

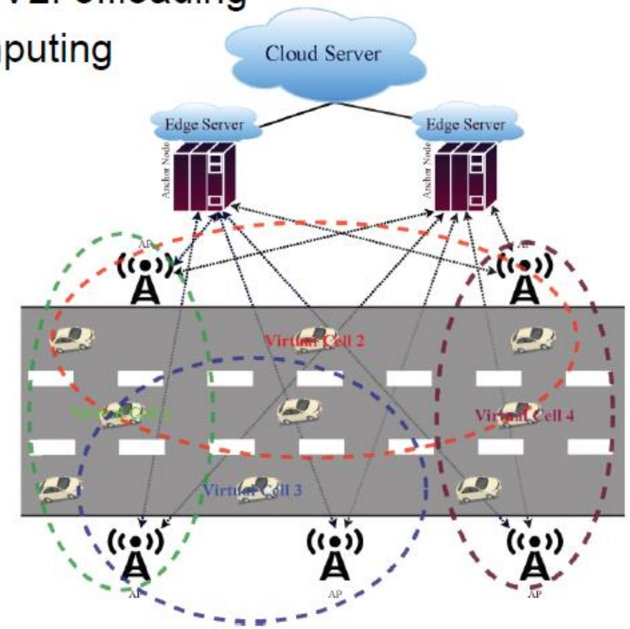
Research Task 3: Computing CAV

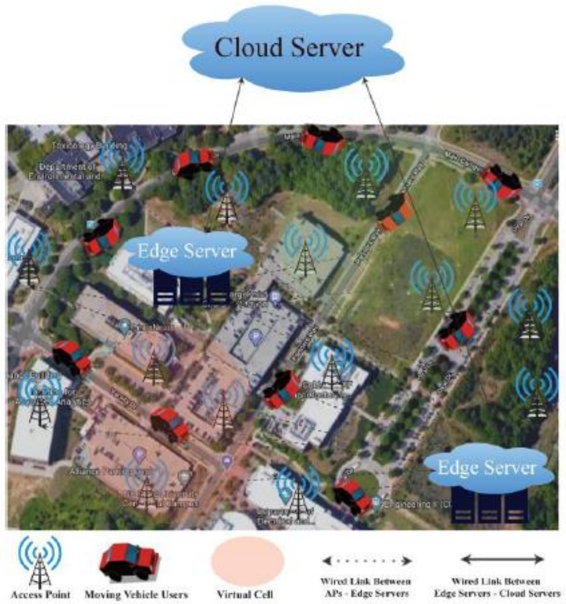
Vehicular Edge Network Slicing: URLLC

- Based on open-loop transmissions & vehicle mobility, jointly optimize virtual cluster association and radio resource allocation for vehicle-centric virtualization
- Distributed multi-agent reinforcement learning
  - Optimal throughput in highway transportation
  - Dynamic eco-routing for CAV infrastructure
  - Reliable & hard-deadline constrained V2I offloading
  - Integrated networking, caching & computing for latency-tolerant services

M. F. Pervej and **S.-C. Lin**, "Eco-Vehicular Edge Networks for Connected Transportation: A Distributed Multi-Agent Reinforcement Learning Approach," in *Proc. of IEEE VTC2020-Fall*, October 2020.

M. F. Pervej and **S.-C. Lin**, "Dynamic Power Allocation and Virtual Cell Formation for Throughput-Optimal Vehicular Edge Networks in Highway Transportation," in *Proc. of IEEE ICC Workshop*, June 2020.



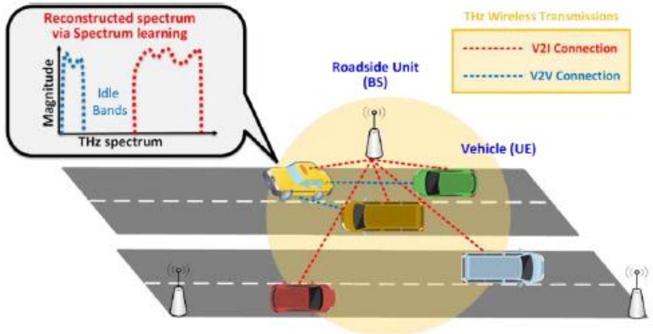


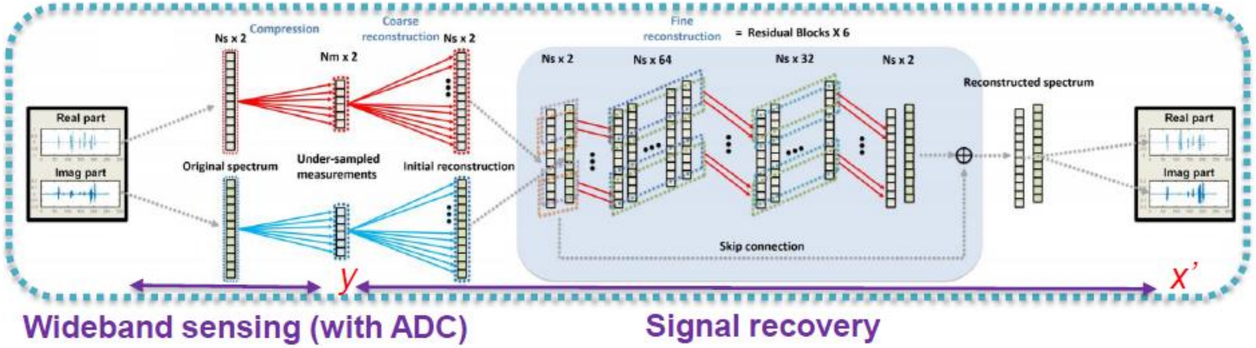
Research Task 3: Computing CAV

Wireless On-Device Learning

C.-H. Lin, **S.-C. Lin**, and E. Blasch, "TULVCAN: Terahertz Ultra-broadband Learning Vehicular Channel-Aware Networking," in *Pro. of IEEE INFOCOM Workshop*, 2021.

- Automatic spectrum analytic: intelligent MODEM for mMTC, V2X
  - Ultra-broadband recognition: THz channel-aware waveform learning (employ E2E deep ResNet for joint spectrum compression & reconstruction)

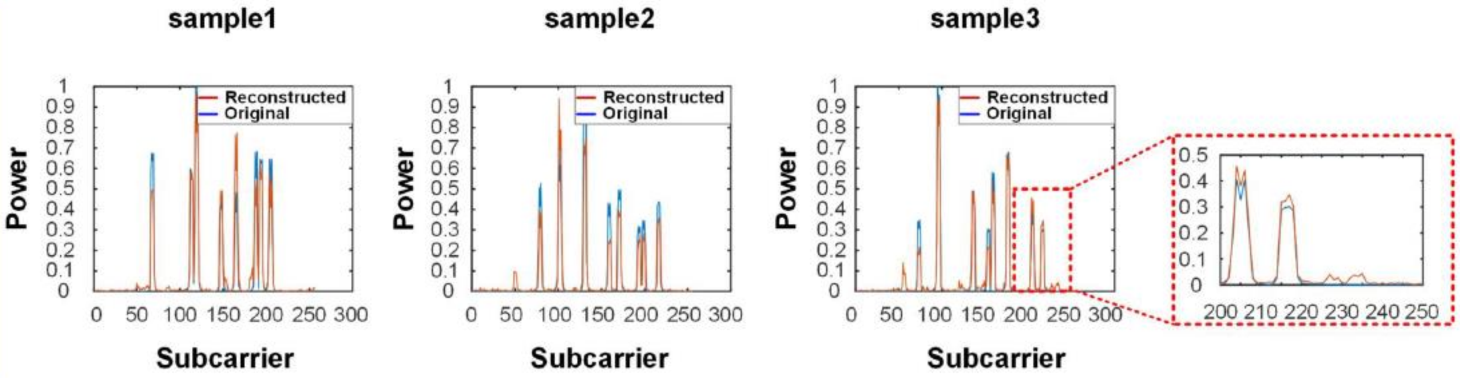




Outperform latest GAN schemes with 26% performance gain and 56% less training overheads

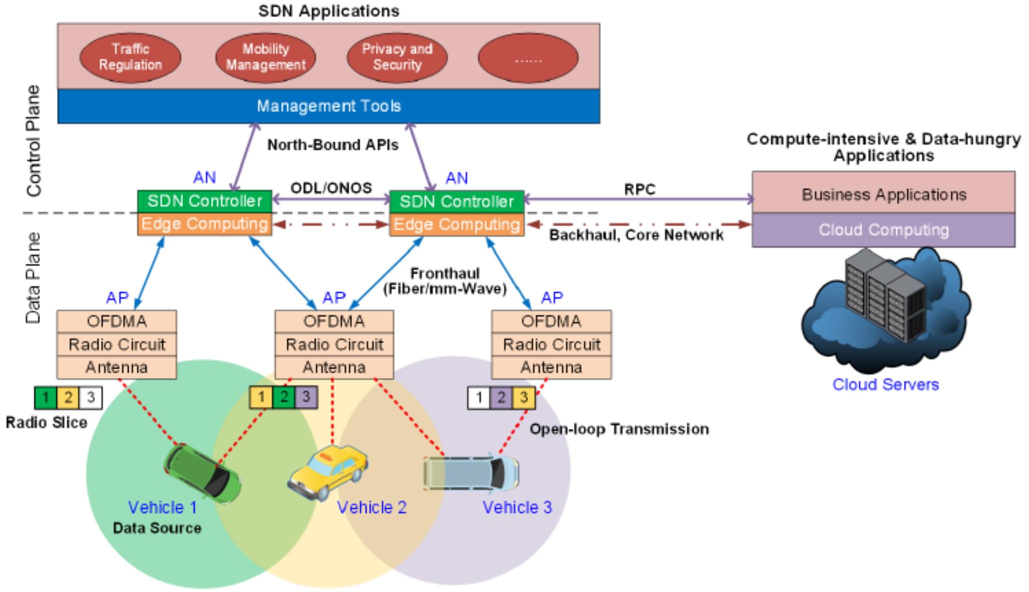
COMPARISON OF SPECTRUM RECONSTRUCTION IN DIFFERENT SNR WITH COMPRESSED RATE = 0.5

SNR (dB)	20		25		30	
Method	GAN	CRNet	GAN	CRNet	GAN	CRNet
MSE	0.0329	**0.0241**	0.0304	**0.0193**	0.0325	**0.0145**
Cosine similarity	0.4659	**0.7828**	0.6588	**0.8315**	0.7511	**0.9107**
SSIM	0.4745	**0.5482**	0.5184	**0.6737**	0.5090	**0.7769**



SD-VEC Testbed Development

1. AN(s) hosting and managing virtual clusters
   - Virtual machines running software-implemented baseband processing functions & PHY/multiple access protocols
2. APs equipped with multiple antennas
   - Controlled by virtual clusters and serve vehicles transmissions
3. Low-latency, high-bandwidth optical fibers
   - Connect APs to AN; support accurate, high-resolution synchronization among APs



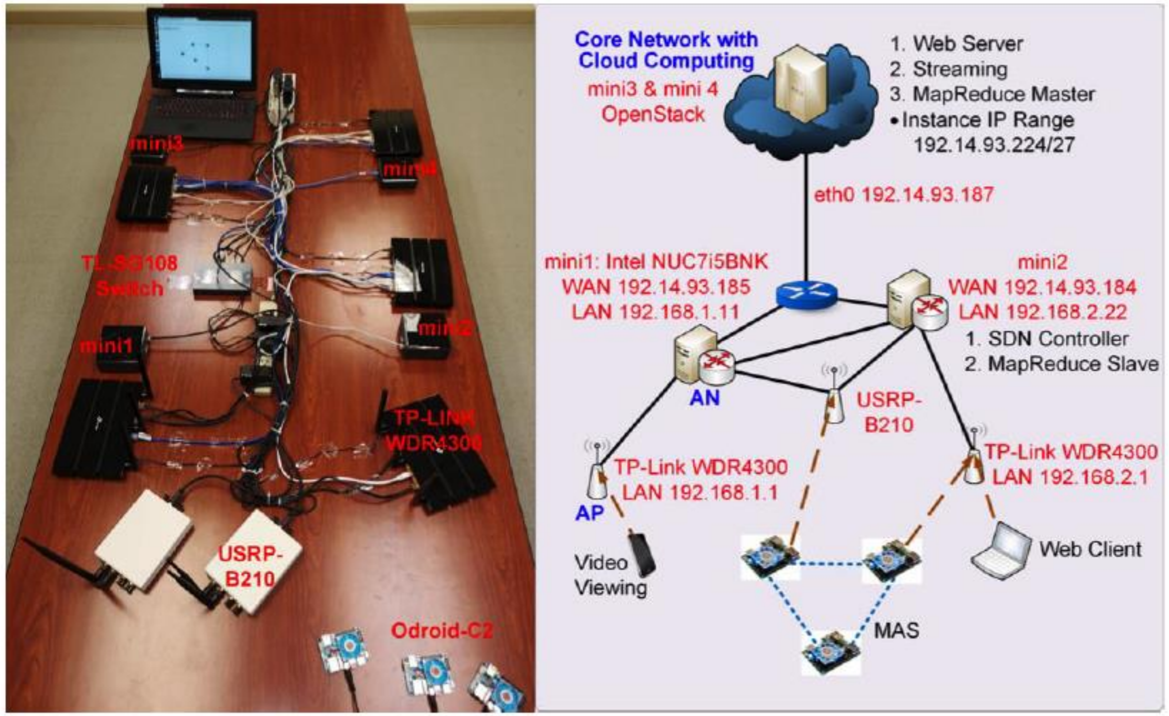
Implementation of SD-VEC architecture

Research Task 3: Computing CAV

An Experimental Testbed in iWN Lab

Fully-functional prototype:

- With 128 MB data chuck and Hadoop application, a small-scale computing testbed provides **53% reduction** in average read/write time



SDN-based edge network and computing platform

- Data sources (with computation workloads)
  - Odroid and Raspberry Pi
- Commercial wireless routers
  - USRP & TP-LINK
- High-performance integrated storage devices
  - Intel NUC + Google TPUs

Simulation Setup for SD-VEC

- Consider real-world vehicular environment to reflect practical network dynamic

  OSM Web Wizard:

  – **O**pen **S**treet **M**ap (OSM): provide road infrastructure

  – **S**imulation of **U**rban **MO**bility (SUMO)

Google Map capture of Downtown Raleigh, NC

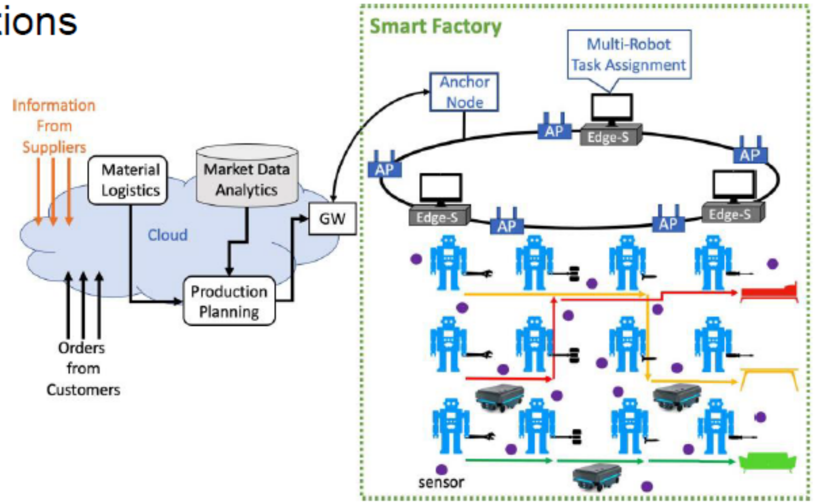
OSM Web Wizard (same Downtown Raleigh area)

Other 5G-Enabled Technology from Our Innovations

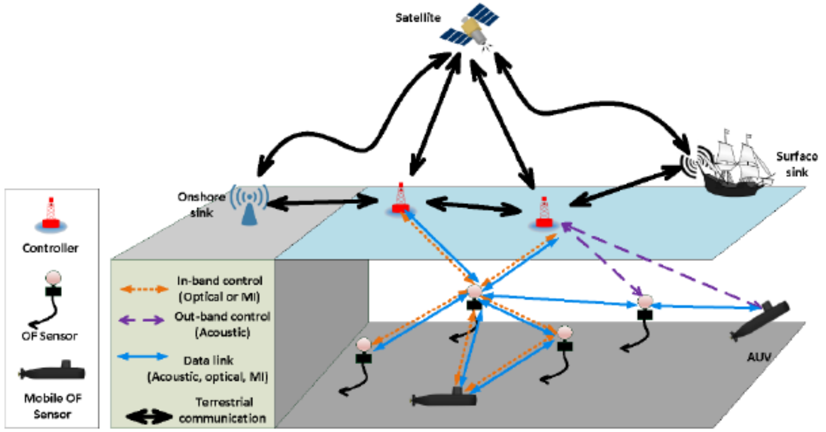
- Scalable, dependable, and controllable Multi-Agent Systems
  - Smart manufacturing: 5G URLLC access for robotics applications

K.-C. Chen, **S.-C. Lin**, C.-H. Liu, A. Molisch, and G. Fettweis, "Wireless Networked Multirobot Systems in Smart Factories," *Proceedings of IEEE*, 2020.

Wireless networked smart factory



- Fast content-delivery infrastructure for untethered 5G VR
- Internet of Underwater Things



I. F. Akyildiz, P. Wang, and **S.-C. Lin**, "SoftWater: Software-Defined Networking for Next-Generation Underwater Communication Systems," *Ad Hoc Networks (Elsevier) Journal*, vol. 46, pp. 1-11, August 2016.

Smart & scalable underwater sensing systems

Research Thrust 2: Next Steps

- Completing Task 2 and 3 in 2020
- Developing Recommendations
- Stakeholder Outreach

Center Admin Activities		FY 2020												FY 2021												FY 2022											
Task	Description	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan
1	Kickoff Meeting and Literature Review																																				
2	Analysis of Existing Programs																																				
3	Low-latency Edge Computing CAV																																				
4	Recommended Program Enhancements																																				
5	Document Research Findings and Develop a Final Report																																				
6	Project Management Activities																																				

NC Transportation Center of Excellence on Connected and Autonomous Vehicle Technology (NC-CAV)

Project 3
Developing and Implementing CAV-UAV Collaboration for Advancing the Transportation Systems

Principal Investigator:
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Research Thrust 3: CAV Applications

Project 3: Developing and Implementing CAV-UAV Collaboration for Advancing the Transportation Systems
Principal Investigator: Abdollah Homaifar (NCA&T)
Other Investigators: Ali Karimoddini, Leila Hashemi (NCA&T), Nagui Rouphail, Chris Cunningham (NCSU) Wei Fan (UNCC)

Scope: Thrust 3 aims to develop and experimentally validate cooperative control techniques for CAVs and UAVs. In particular, Thrust 3 will develop cooperative control techniques for On-Demand mobility applications, and prototype a testbed for a network of CAVs to implement emergent applications of CAVs. We will explore the application of UAVs for transportation systems like aerial traffic monitoring and accident, or emergency management.

Objectives:

- Develop Cooperative control of heterogeneous CAVs and UAVs for on-demand mobility applications
- Prototype a testbed for a network of CAVs
- Explore aerial monitoring using CAVs

Project 3: Research Tasks and Timeline

Center Admin Activities		FY 2020												FY 2021												FY 2022											
Task	Description	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan
1	Literature Review																																				
2	CAVs for On-Demand Mobility																																				
3	Developing a CAV Testbed																																				
4	Aerial Trffic Monitoring																																				
5	Field Experiments and Testing																																				
6	Document Research Findings and Develop a Final Report																																				
7	Project Management Activities																																				

CAVs for on-demand mobility

Task 2 of Thrust 3

NC-CAV Center

Research Thrust 3: CAV Applications

Research Questions include

How to:

- Minimize traffic congestion due to increased traffic volume
- Optimally assign passenger requests to vehicles
- Optimally route vehicles from pickup points to their destinations
- Compute rebalancing routes for unassigned or empty vehicles

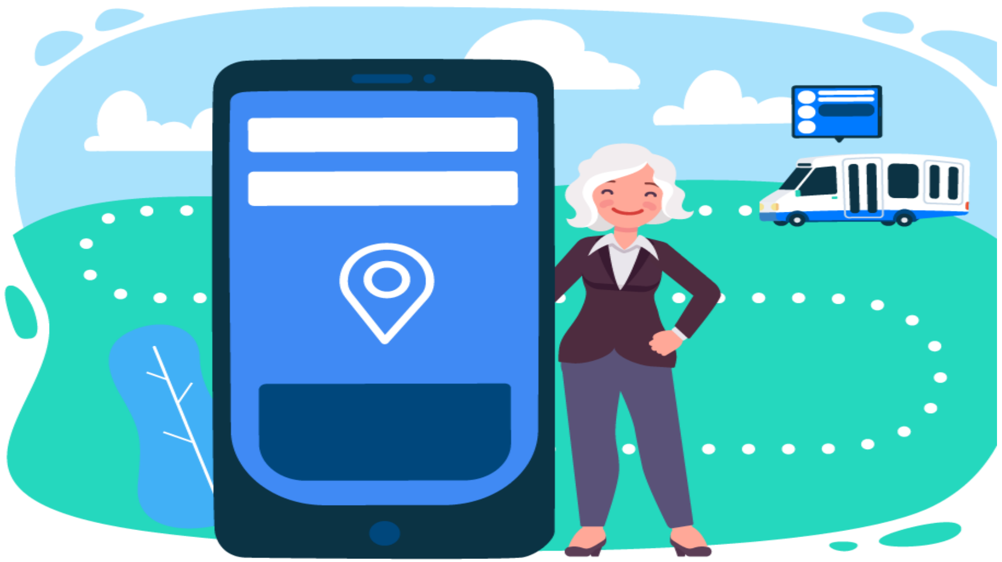
Challenges/gaps include

- Dealing with the dynamic and uncertainty of customer demand
- Autonomous navigation of CAVs in a complex dense urban environment
- Scalability and computational efficiency of algorithms

Proposed possible solutions include

- Employing analytical, scalable and computationally efficient algorithms
  - Graph theory, mixed integer programming ,combinatorial optimization
- Employing a machine learning technique for traffic volume prediction
  - Extreme gradient boosting (xgboost)

Mobility on Demand



- **Mobility on demand (MOD)** is simply a concept which provides a platform for consumers or individuals to access mobility, goods and services on demand by dispatching or making use of shared mobility.
- It provides individuals with varying transportation modes to make their journeys more efficient
- MOD services can be:
  - MOD passenger mobility
  - MOD courier services
- MOD passenger services include:
  - Bikesharing, carsharing, ridesharing (i.e., carpooling and vanpooling), scooter sharing, shuttle services, Urban Air Mobility and public transportation.
- MOD courier services include:
  - App-based delivery (also known as Courier Network Services or CNS), robotic delivery and aerial delivery (e.g., drones)

Traffic Volume Prediction

Figure source: https://www.youtube.com/watch?v=jM4nfgo4MQ4

Traffic volume is the number of vehicles that pass a point on a road within a given time interval.

It may be expressed in terms of annually, daily, hourly or sub-hourly periods.

Traffic volume prediction enables traffic managers to make appropriate plans to mitigate traffic congestion and minimize the overall travel delay

Literature Review

Machine Learning (ML) Approaches

Classical ML Techniques -

Support Vector Machines and K-Nearest Neighbors

Pros

- Generate more stable and accurate prediction results

Cons

- Computationally inefficient

Deep Learning Techniques -

Long short-term memory (LSTM), deep neural network

Pros

- Generally, exhibits better performance

Cons

- Computationally inefficient

Statistically-based Approaches

Autoregressive Integrated Moving Average (ARIMA) model -

Pros

- Theoretically well defined
- Easier to be interpreted

Cons

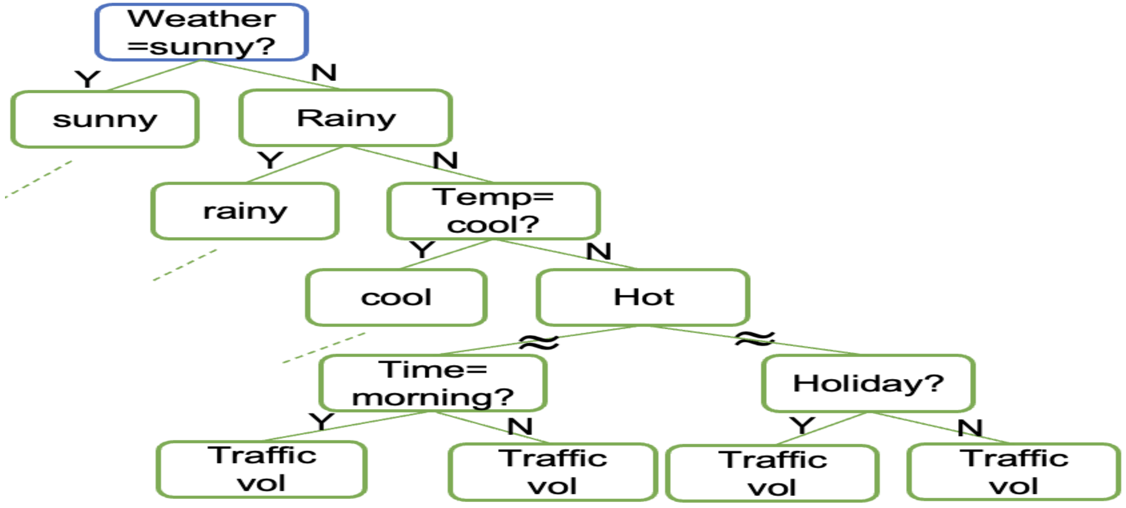
- Does not exhibit good performance and in general solutions are unstable

Methodology

- Xgboost is a tree boosting algorithm that is highly scalable, computationally efficient and exhibits high performance.
- Lasso regularization was used to avoid overfitting and increase performance by minimizing the cost function below:

$$C = \sum_i l(y_i, \hat{y}_i) + \sum_k \Omega \Rightarrow \textbf{Regularization term}$$

$$where\ \Omega = \gamma T + \frac{1}{2}\alpha \sum_j |w_j| \Rightarrow \textbf{LASSO term}$$



Xgboost prediction steps

l is the loss function; T is the number of leaves in each tree, w is the weight of each leaf, Ω penalizes the model's complexity, γ is the minimum loss reduction for splitting a node, α is a regularization penalty

- Then compare traffic volume prediction accuracy of xgboost with existing methods.

Traffic Volume Data

- Traffic volume data provided by the Minnesota Department of Transportation on UCI Machine Learning Repository was used in this work.
- It consists of hourly traffic volume on Interstate 94 Westbound which lies between Minneapolis and St. Paul, Minnesota.
- It was collected between the periods of 2012 and 2018.
- The data consists of 48204 observations and eight attributes.
- Attributes include holiday, temp, rain_1h, snow_1h, % clouds_h, weather_main, weather_description, date_time.

A section of I-94, Minnesota

Cumulated Prediction Results

- **Comparing the performance of nine machine learning models**

Model	**R^2**	**RMSE**	**MAE**
SVR	0.8037	0.4455	0.3153
KNN	0.7280	0.5244	0.3830
DT [3]	0.9439	0.2380	0.1380
RF [2]	0.9744	0.1608	0.0965
GBM [2]	0.9346	0.2570	0.1779
FCDNN [2]	0.9691	0.1767	0.1181
LSTM [4]	0.9613	0.1917	0.1254
XGBOOST	**0.9823**	**0.1336**	**0.0849**

R^2: coefficient of determination
RMSE: root mean square error
MAE: Mean Absolute Error

Note: these results are the average of 15 runs

FCDNN: fully connected deep neural network
GBM: Gradient Boosting Machine
DT: Decision Trees
RF: Random Forest
LSTM: Long Short-Term Memory
XGBOOST: Extreme Gradient Boosting

Statistical significance

Wilcoxon Signed-rank test

- Tests whether two groups of observations are statistically different or not
- When significance level, $\alpha >$ p-value, there is a statistical difference, given that α=0.05

Model	p-value	interpretation
FCDNN	0.00	statistically different
RF	0.00	statistically different
SVM	0.00	statistically different
KNN	0.00	statistically different

Statistical significance of xgboost compared with algorithms used in the literature

Conclusions and Future Work

Conclusions

- Research question 1 was addressed by investigating various machine learning techniques for traffic volume prediction
- Xgboost exhibited better performance compared with other models
  - Therefore, xgboost could be used for traffic volume prediction in order to minimize traffic congestion

Future work

- Explore other regularization techniques for the traffic volume prediction problem
- Investigate the impact of holiday and weather features on traffic volume
- Employ an analytical, scalable and computationally efficient algorithm for the problem of optimal assignment and routing
- Continue with the work on building a CAV testbed for mobility on demand applications

Development of a CAV Testbed

Task 3 of Thrust 3

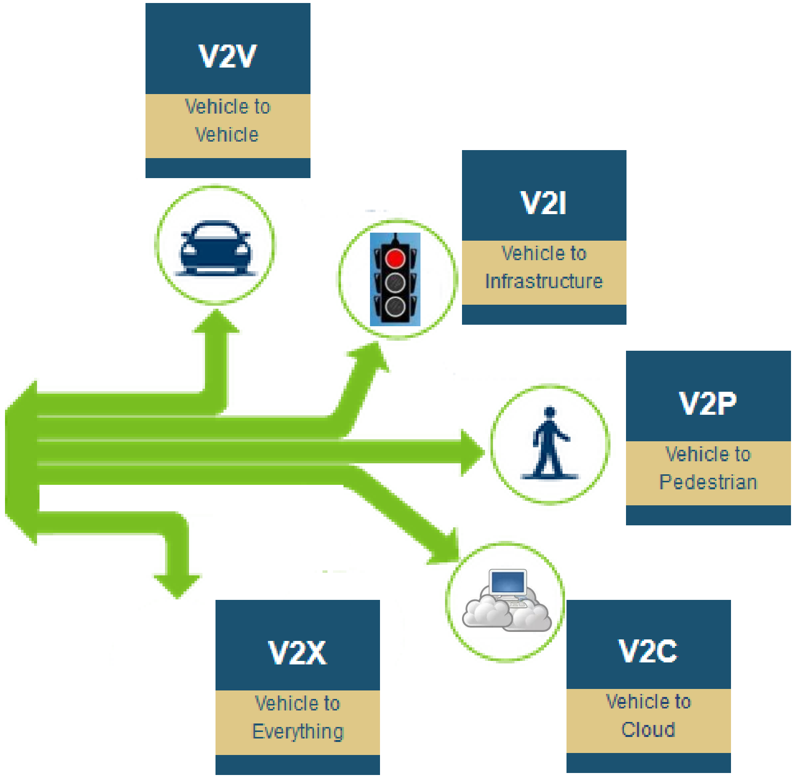
NC-CAV Center

Muhammad Islam, Redwan Newaz, Benjamin Lartey,

Ali Karimoddini, and Abdollah Homaifar

CAV Overview

Connected and Autonomous Vehicles (CAVs) are autonomous vehicles that are based on communication between vehicle-to-vehicle (V2V), vehicle to roadside infrastructure (V2I), vehicle to the "Cloud" (V2C), vehicle to pedestrians (V2P), and Vehicle to Everything (V2E) .



Advantage of CAV Technology Adoption

Sharing and processing data with other vehicles and road or network infrastructure

Providing on-demand-mobility solutions

Improve the safety and performance and reducing crashes

New Models for Vehicle Ownership

Reduce Travel time

New Business Models and Scenarios

Improved Energy Efficiency

Environmental Benefits

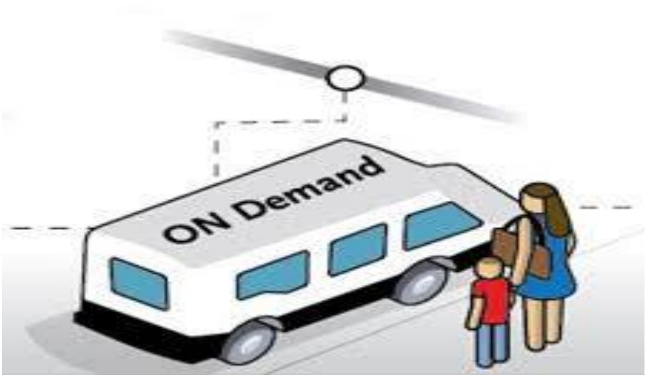
Example of CAV Applications

Intersection Collision avoidance & safe and smooth flow utilizing signal information (I2V)

Cooperative Advanced Vehicles (V2V and V2P) for handling non-signalized intersections

Smart transportation with ACC/CACC (I2V, V2V) for congestion mitigation

On-demand mobility service



CAVs State of the Art

2015
Investigating communications performance for CAV by Joyoung et. al

2016
Valuing the Safety Benefits of Connected And Automated Vehicle Technologies by Tianxin et.al

2017
Developments in connected and automated vehicles by Yang et.al

2018
Control of Connected and Automated Vehicles by Jacopo et. al

2019
Cooperative Connected Autonomous Vehicles (CAV) by Jianhua et. al

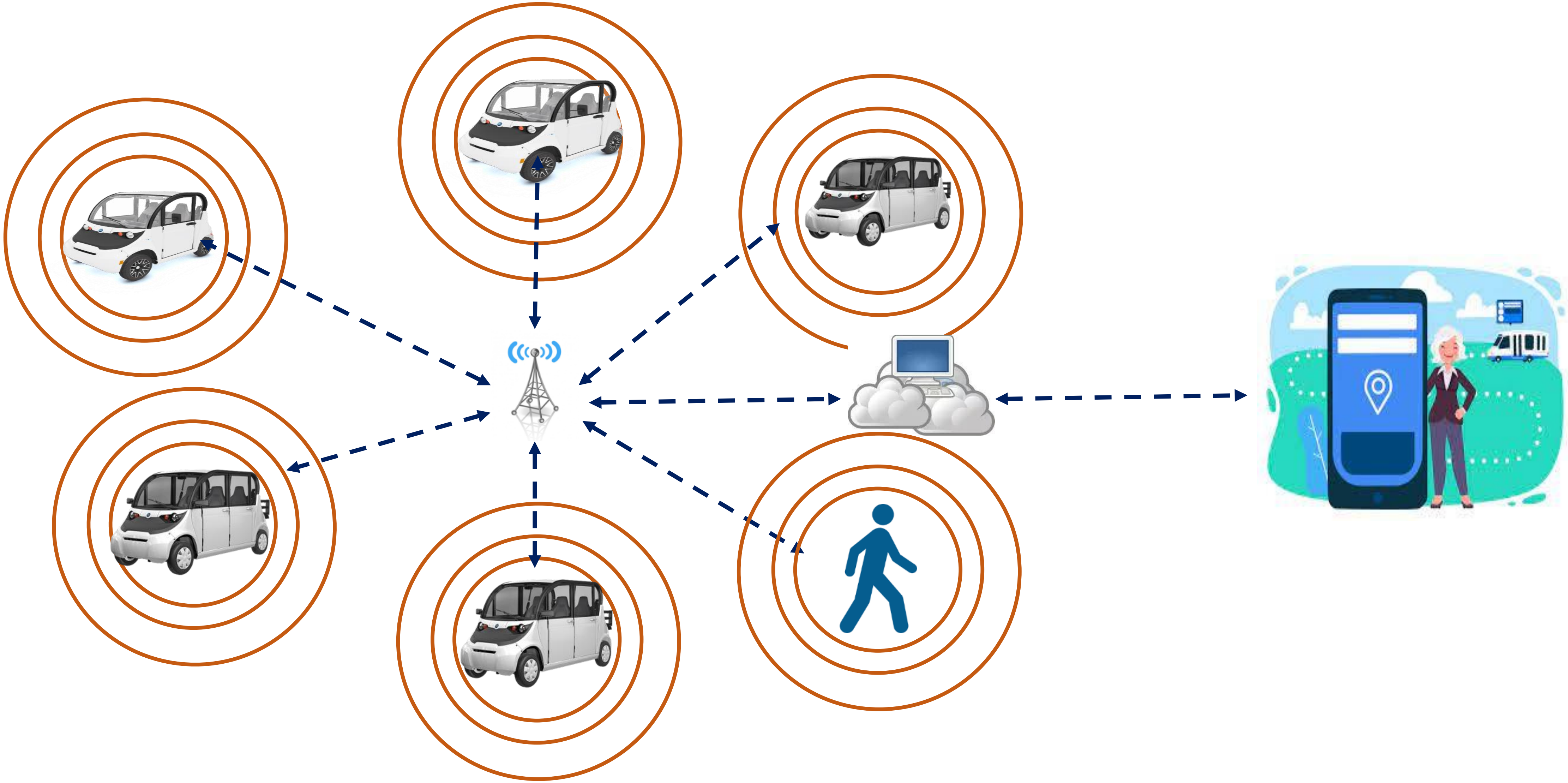
2020
Big Data safety analytics for CAV by Yanqi et.al

In literature, we have seen component-wise discussion on CAV since most of CAV technologies are still under development

CAVs State of the Practice

- Most studies are focusing on theoretical impacts of CAV deployments.
- Most experimental studies focus on
  - AVs development and deployment, and most effort is on regular cars versus buses, vans, etc.
  - Developing infrastructure for connection to AVs
    - The DOT Connected Vehicle Test Bed in in Novi, Michigan: It consists of a network of 50 roadside equipment (RSE) units installed along various segments of live interstate roadways, arterials, and signalized and unsignalized intersections. These RSEs communicate messages over 5.9 Ghz Dedicated Short Range Communication (DSRC).
    - PennSTART**:** PennDOT and PSU have partnered to develop training and testing facility.
    - CAV Infrastructure at NC**:**
      - AV Testing on the Western Wake Freeway/Triangle Expressway for testing truck platooning
      - Signal Phasing and Timing (SPaT) Challenge for testing coordinated signal systems and broadcasts to drivers at more than 20 intersections on NC55 in Cary.
- There has been some simulation-based efforts for CAV deployments:
  - Federal Highway Administration (FHWA) hardware in the loop (HIL): This HIL is planned to be used for testing architecture for vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) applications. The selected case study for each HIL architecture is signalized intersection approach and departure (SIAD) and cooperative adaptive cruise control (CACC).
- There exists very few experimental testbeds for CAVs primarily on testing platooning or cooperative adaptive cruise control
  - Platooning of trucks demonstrated by Volvo
  - Cooperative adaptive cruise control of Chevy Bolts demonstrated by GM

Our Proposed CAV Testbed



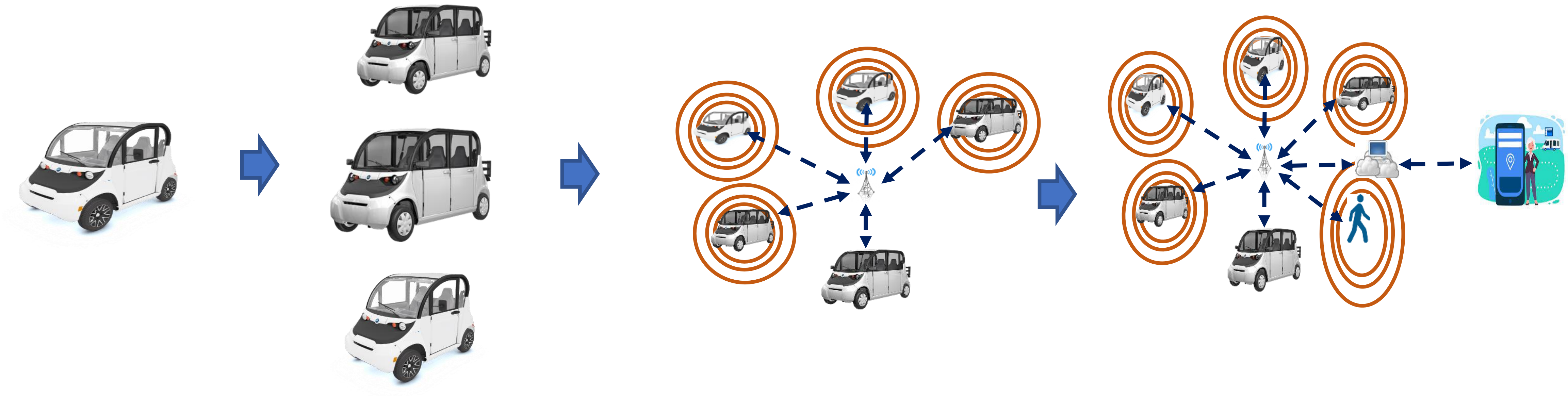
Roadmap for Developing the Proposed CAV Testbed

Prototyping an AV using GEM e2

Developing several AVs using GEM e2 and GEM e6

Make them connected to each other

Make them connected to the cloud and users



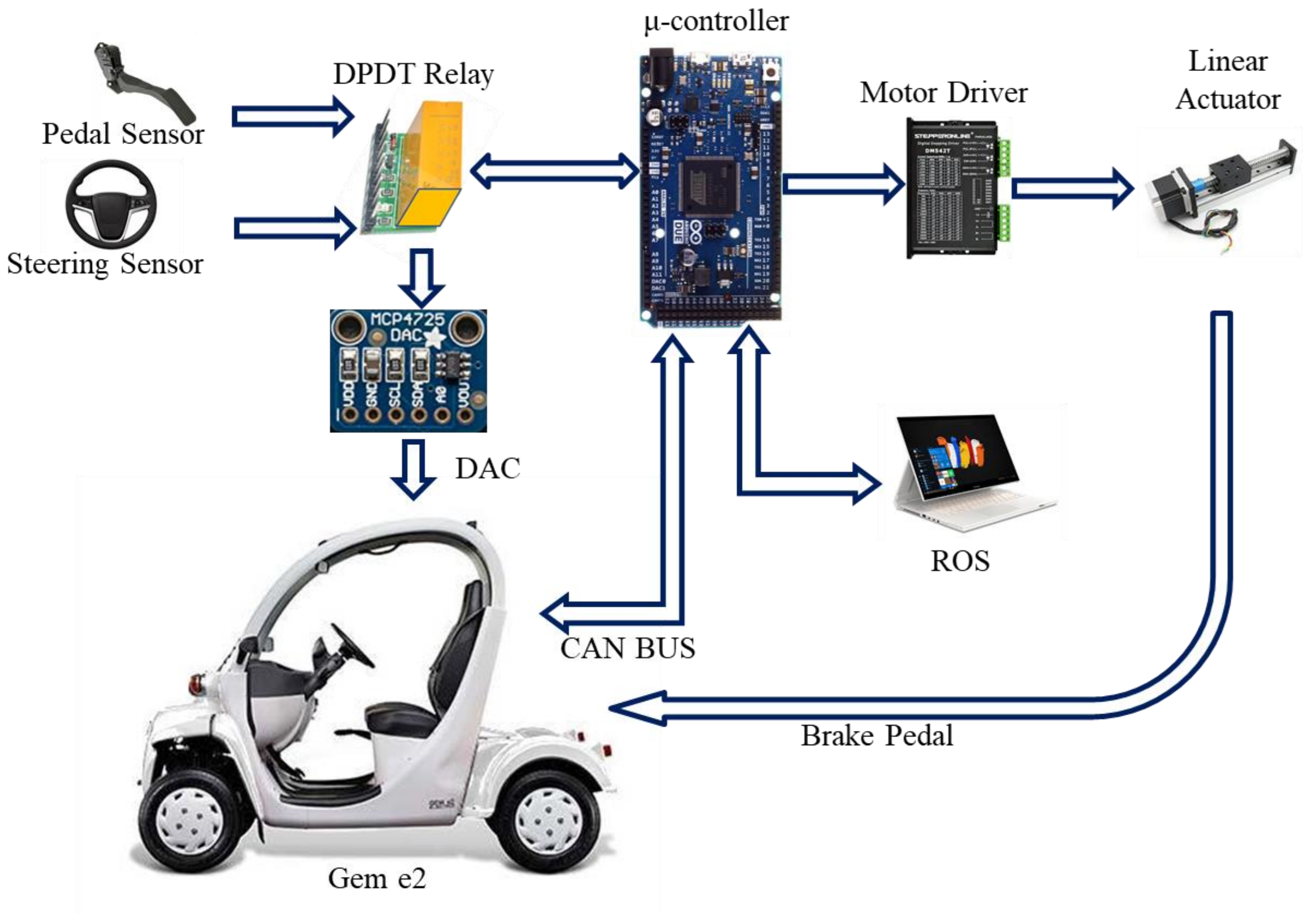
Prototyping an AV using GEM e2

Steps need to make a Gem e2 as an autonomous vehicle:

- Modifying the GEM e2 to make it Drive-by-wire
- Add sensors (Radar, Lidar, GPS, camera, etc)
- Develop sensor fusion and perception algorithms
- Develop control, path planning, and routing algorithms

Modifying the GEM e2 to make it drive-by-wire

- **Step 1:** Accelerator pedal control using a drive-by-wire technique
- **Step 2:** Brake pedal control using a drive-by-actuator technique
- **Step 3:** Steering wheel control using a drive-by-wire technique



Our Progress: drive-by-wire GEM e2

- Accelerator Pedal control (Drive-by-wire)
- Brake Pedal control (Drive-by-actuator)
- Joystick Interface

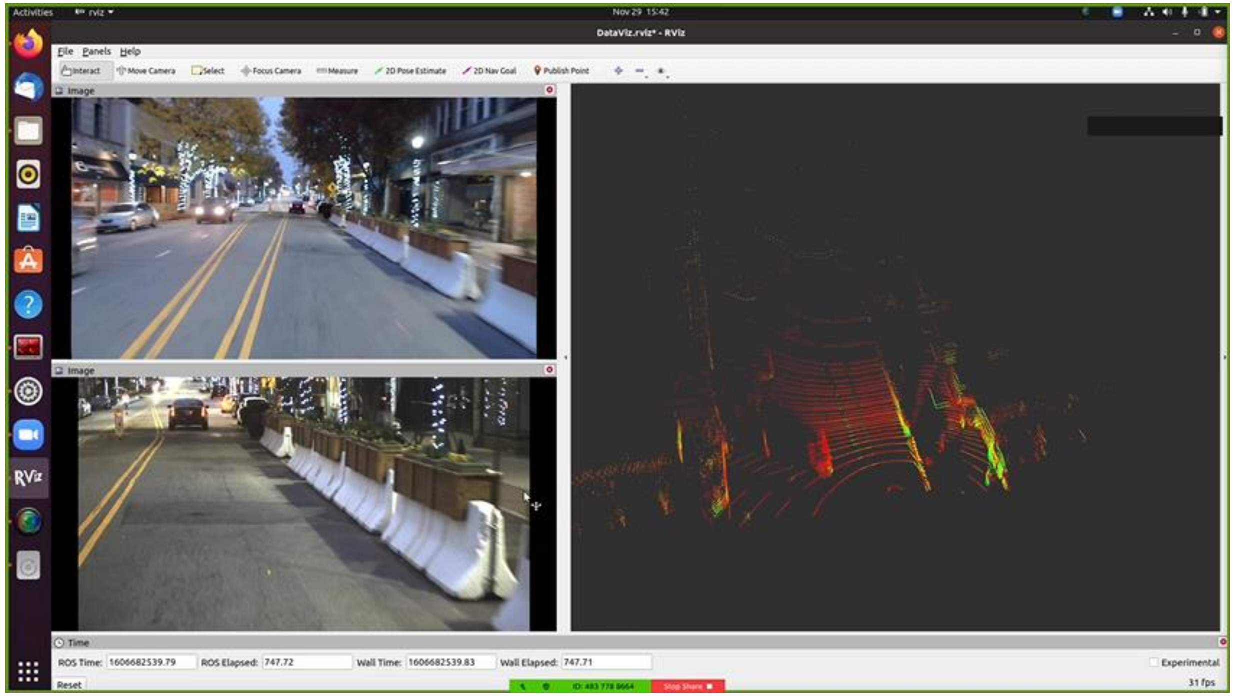
Our Progress: Perception System Development

- Deep Learning-based Pedestrian Detection
- Occlusion Handling by classifying body-parts

M. M. Islam, A. Al Redwan Newaz, B. Gokaraju and A. Karimoddini, "Pedestrian Detection for Autonomous Cars: Occlusion Handling by Classifying Body Parts," *2020 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, Toronto, ON, Canada, 2020, pp. 1433-1438, doi: 10.1109/SMC42975.2020.9282839.

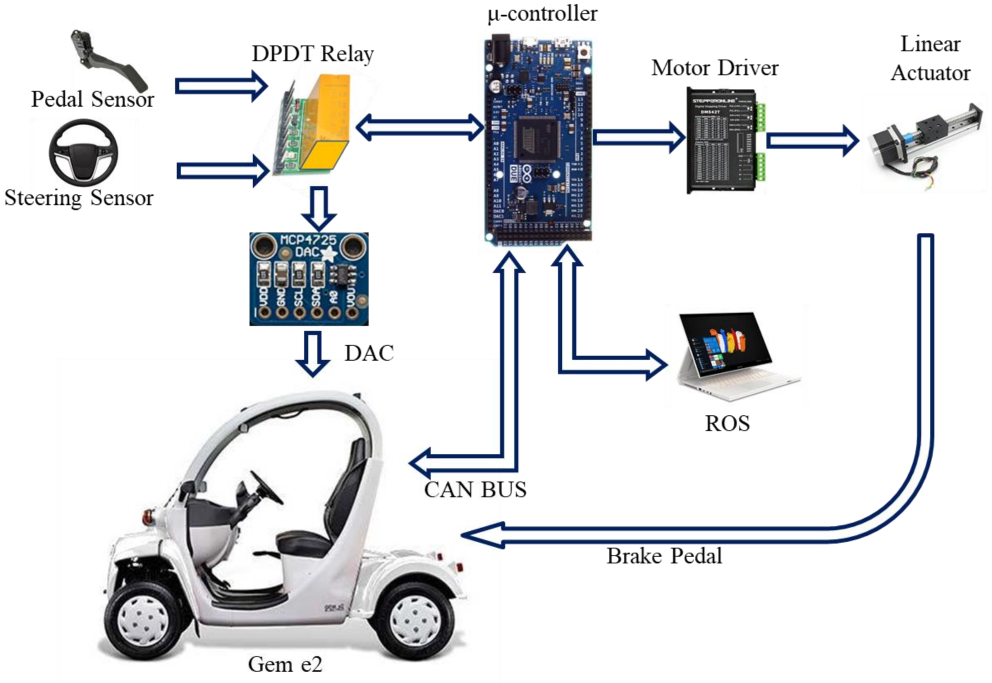
Our Progress: Perception System Development

Multi-modal Sensor Dataset Collection



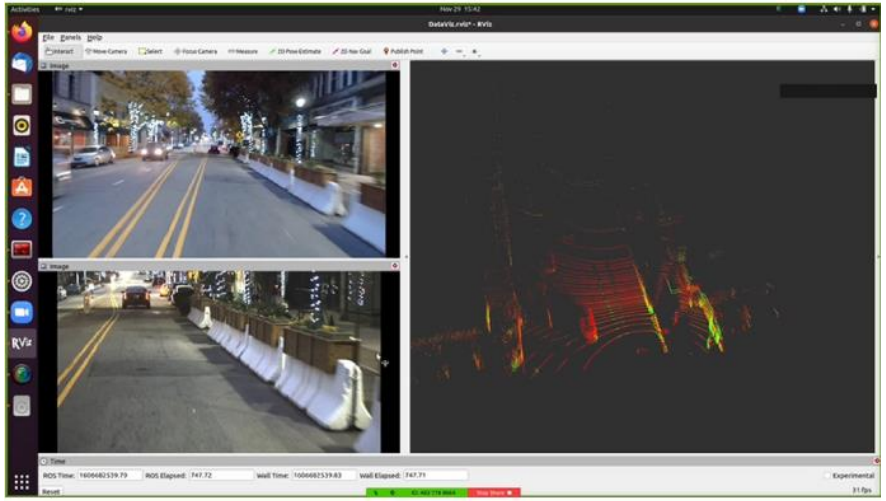
- Two front facing cameras
- 180-degree Lidar point cloud data
- ROS bag for time synchronization

Future work: Complete the drive-by-wire developments



- **Step 1:** Accelerator pedal control using a drive-by-wire technique (completed)
- **Step 2:** Brake pedal control using a drive-by-actuator technique (completed)
- **Step 3:** Steering wheel control using a drive-by-wire technique (on-going)

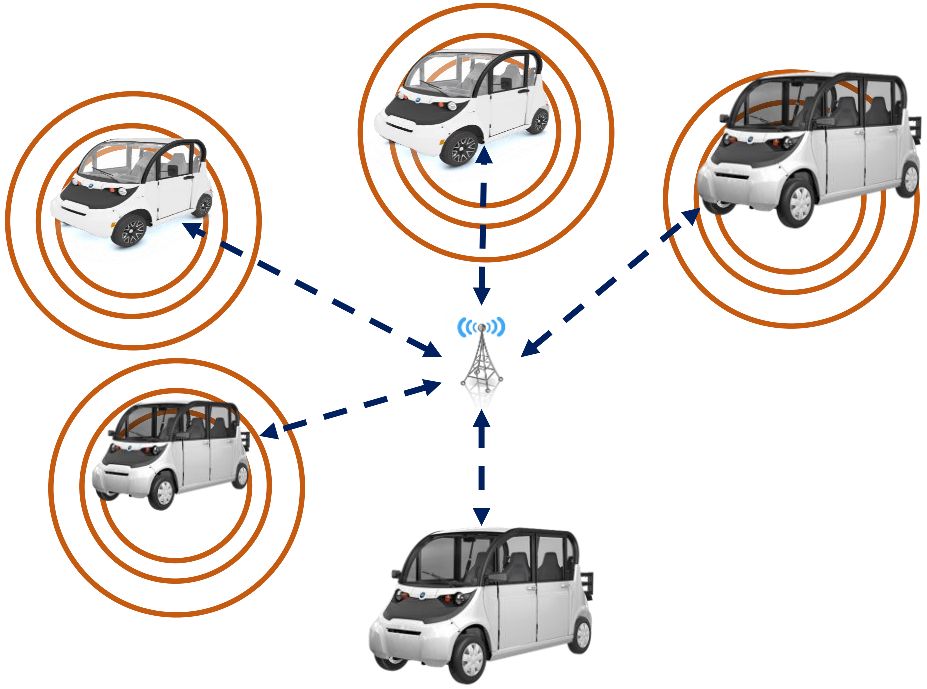
Future work: An enhanced perception system



- Implementation of semantic segmentation for the driving scenario
- Integration of multi-modal sensor
- Sensor fusion using Lidar and camera sensors

Future work: Make them connected!

Vehicle networking and cloud services



- We are planning to use Verizon network to connect the vehicles to each other and to the cloud
- We are planning to use CARMA kit for V2V and V2I communications

NC Transportation Center of Excellence on Connected and Autonomous Vehicle Technology (NC-CAV)

Education and Outreach

NC-CAV: Education and Outreach

- We developed an Autonomy Certificate at NC A&T graduate program. The certificate has 3 tracks including:
  - **Track 1: Smart Transportation and Autonomous Vehicles**
  - Track 2: Intelligent Control Systems
  - Track 3: Cyber Physical Systems

- We developed an Autonomy Certificate at NC A&T undergraduate program. The certificate has 3 tracks including:
  - **Track 1: Smart Transportation and Autonomous Vehicles**
  - Track 2: Smart Manufacturing and Automation
  - **Track 3: Unmanned Aerial Vehicles**

Both certificates have been approved by ECE department and the College of Engineering at NCA&T State University and are passed on to the University-level administration for seeking final approvals, targeting for offering in Fall 2021.

NC-CAV: Education and Outreach

Co-organized the “IT! It is for Girls” Summer Camp

- The NC-CAV Center team co-organized the “IT! is for Girls” summer camp in collaboration with the American Association of University Women (AAUW) with the objective of inspiring young girls to pursue interests in STEM education and transportation technologies in the future.

NC-CAV: Education and Outreach

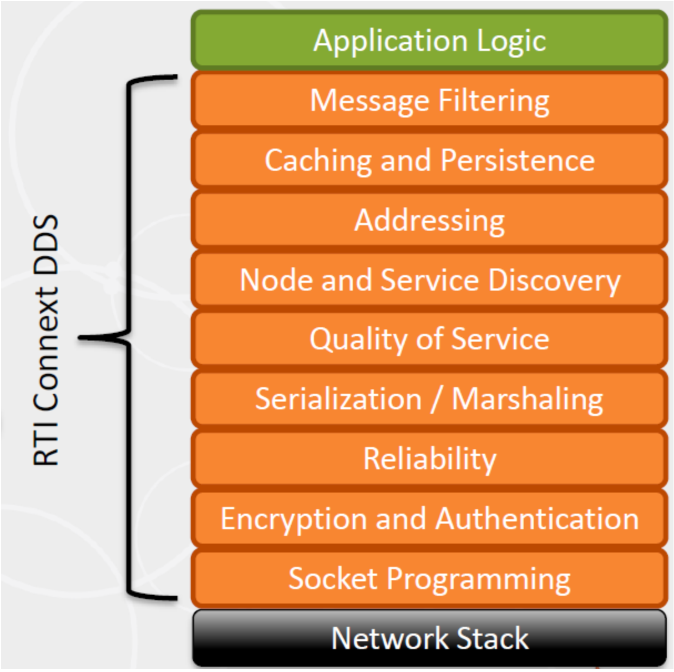
Mohammad Islam, a graduate student member of NC-CAV Center, was awarded for outstanding presentation for his work entitled "*Pedestrian Detection for Autonomous Cars: Occlusion Handling by Classifying Body Parts*" at the Next-Generation Transportation Systems (NGTS-2020) Conference which was held in Dec 2020.

NC-CAV: Education and Outreach

Organized two workshops on RTI Software Framework.

Workshop 1 (Jan 10, 2021): introductory training including the basic functionality of Connext DDS as well as the best practices to use the rich set of RTI tools efficiently.

Workshop 2 (Feb 23, 2021): integration of Connext DDS and ROS. RTI works on the mapping layer for Robot Operating Systems (ROS) and the user may have some ROS2 nodes with DDS to enable seamless communication between ROS2 and DDS.



The Connext DDS RTI involves the implementation of application logic, message filtering, caching and persistence, addressing, node and service discovery, Quality of Service, serialization/Marshaling, reliability, encryption and authorization, socket programming, and network stack, which all are needed for reliable communication between CAVs' components.

NC-CAV: Education and Outreach

- Supported a senior design team which was placed first in the College of Engineering Competition in 2020.
- The group was placed first in the 2020 Senior Design Competition, in NCA&T College of Engineering.




NC-CAV: Education and Outreach

Supported the Aggies Autonomous Auto (A3) team in the Autodrive Challenge

- Nc-CAV supported the Aggies Autonomous Auto (A3) team in the Autodrive Challenge in June 2020.
- Organized by SAE International and General Motors, the Autodrive Challenge is a four-year competition to develop and demonstrate a fully autonomous passenger vehicles.
- The technical goal of the competition is to navigate an urban driving course in an automated driving mode as described by SAE Standard (J3016) level 4 definition by year three.
- Year 4 (2021) is the last year of this inaugural series of the AutoDrive Challenge™ competition and will be held on June 5-14, 2021 in Ann Arbor, Michigan.

NC Transportation Center of Excellence on Connected and Autonomous Vehicle Technology (NC-CAV)

Research Dissemination Activities

NC-CAV: Research Dissemination Activities

NC-CAV Seminar Series

- NC-CAV organizes cross-disciplinary seminars and workshops in different aspects of CAV infrastructure, development, and deployment.
- The goal is to create an interactive forum as an environment for sharing recent research results and discussing various CAV and autonomy-related problems from different angles by participants with different backgrounds and expertise from academia, industry, government, and national labs.

NC-CAV Future Seminar Series Sessions

Date	Presenter	Tentative Title
3/26/2021	Dr. Shih-Chun Lin	Machine Learning-Enabled and Ultra-Law Latency Connected Transportation
4/30/2021	Dr. Ali Hajbabaie	TBD
15/28/2021	Mr. Bob Leigh	Data-Centric Architecture: The foundation to CAV design and performance
6/25/2021	Dr. Ayman Habib	TBD
7/30/2021	Dr. Steven Jiang	Impact of Automated, Connected, Electric, and Shared Vehicles on Transportation Revenue Collection
8/27/2021	Dr. Wei Fan	Disruptive Technologies in Transportation: Implications and Opportunities

NC-CAV Past Seminar Series Sessions

Date Held	Presenter	Title
9/25/20	Dr. Abdullah Al Redwan Newaz	Anomaly Detection for Autonomous Driving
10/30/2020	Mr. Thomas Chase	Introduction to Connected Traffic Signals
12/4/2020	Dr. Nicolas Norboge	Transportation Funding in a World of CAV: Implications and Lessons Learned from COVID that are instructive?
1/29/2021	Mr. Tesfamichael Getahun	Lane Detection for Autonomous Cars
2/26/2021	Dr. Daniel Findley	Public Perceptions of Transportation Fees and Taxes

NC-CAV: Research Dissemination Activities

NC-CAV Publications

- [1] Muhammad Mobaidul Islam, Abdullah Al Redwan Newaz, Balakrishna Gokaraju, and Ali Karimoddini, “Pedestrian Detection for Autonomous Cars: Occlusion Handling by Classifying Body Parts,” Proc. of 2020 the IEEE SMC Conference.

- [2] Md Ferdous Pervej and Shih-Chun Lin, “Eco-Vehicular Edge Networks for Connected Transportation: A Distributed Multi-Agent Reinforcement Learning Approach,” Submitted to the 2020 IEEE 92nd Vehicular Technology Conference: VTC2020.

- [3] Shih-Chun Lin, Kwang-Cheng Chen, Ali Karimoddini, and Nicola Rohrseitz “SD-VEC: Distributed Computing Architectures for Ultra-Low Latency Connected Transportation,” Submitted to the IEEE Communications Magazine.

- [4] Kwang-Cheng Chen, Shih-Chun Lin, Jen-Hao Hsiao, Chun-Hung Liu, Andreas F. Molisch, and Gerhard Fettweis, “Wireless Networked Multi-Robot Systems in Smart Factories,” PROCEEDINGS OF THE IEEE.

- [5] Li Song, and Wei Fan, “CAV Impacts on Traffic Intersection Capacity,”, Publisher: NC-CAV, Report No. TCE2020-03-001, January 2021.

- [6] Morgan Crowder, Steven Jiang, James Poslusny, Nicolas Norboge, Steve Bert, Daniel Findley, “Impacts of Automated, Connected, Electric, and Shared Vehicles on Transportation Revenue Collection,” Publisher: NC-CAV, Report No. TCE2020-03-002, January 2021.

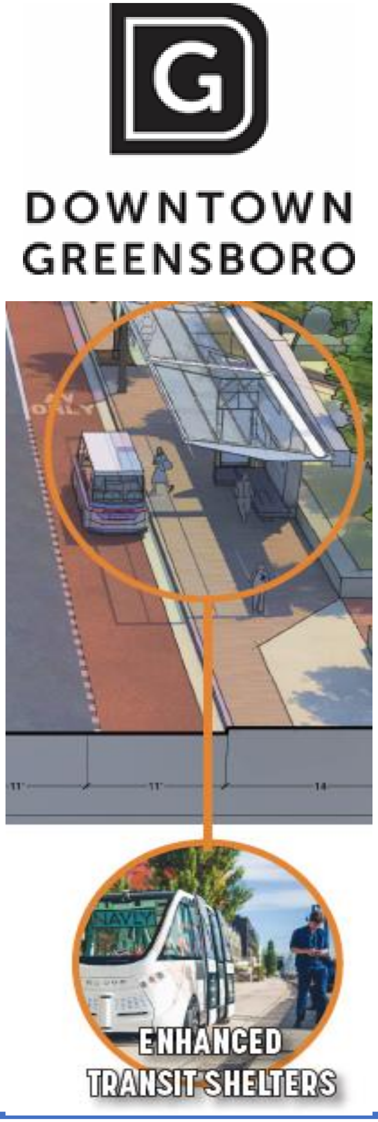
NC Transportation Center of Excellence on Connected and Autonomous Vehicle Technology (NC-CAV)

Engagement of Stakeholders and Industrial Partners

NC-CAV: Stakeholder Engagement Activities

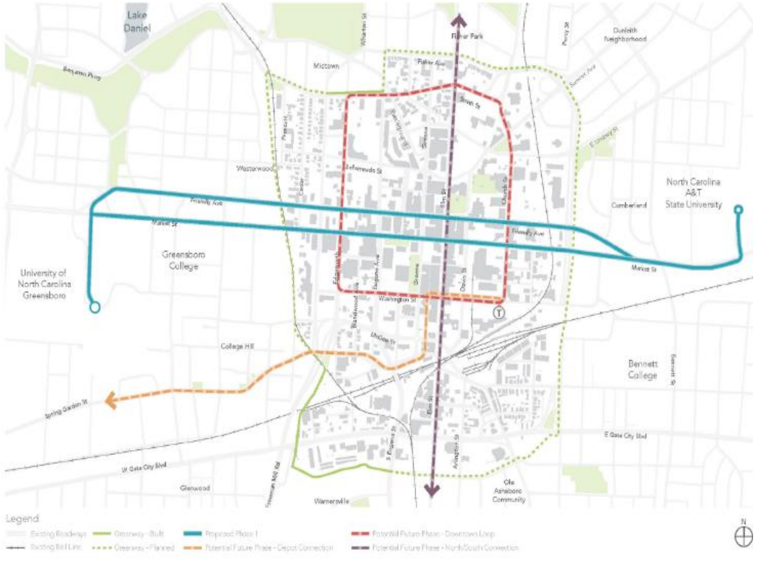
- **North Carolina Department of Transportation (NCDOT)**
- Regular collaboration and communication between NC-CAV and NCDOT Staff is going on to ensure that NC-CAV outcomes will be aligned with the NCDOT vison.
    - The NC-CAV research group had a meeting with Dr. Joe Hummer, Mr. Neil Mastin, and Mr. Mustansir Kadibhai from NCDOT in February 2021.
    - NCDOT's input and guidance was sought on one of the NC-CAV case studies
    - Discussions was carried out about the possible choices of intersections available for conducting the NC-CAV research
    - Consensus was established that the selected intersection should have traffic volume and lane configuration data (e.g., number of lanes and lane use information) available for the modeling purposes

NC-CAV: Stakeholder Engagement Activities



DGI is now onboard!

- NC-CAV Center started collaboration with City of Greensboro Department of Transportation and Downtown Greensboro Inc.
  - Opportunities are being explored for Improving access and mobility to and through Greensboro downtown by using self-driving shuttles being developed under NC-CAV Center
  - Pilot programs and phasing approaches have been discussed for testing and adapting shuttle routes to maximize efficiency, accommodate major events, and serve new destinations
  - A route (shown in green) that connects the East-West connections between UNC Greensboro, Downtown, and North Carolina A&T was selected as a candidate route for self-driving shuttles



Autonomous Shuttle Connector Potential Route

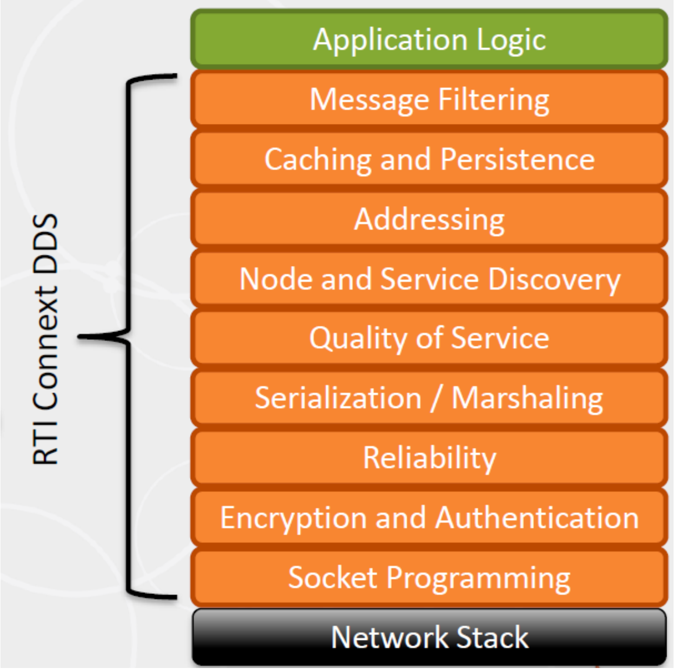
NC-CAV: Stakeholder Engagement Activities

- **Verizon is now onboard!**
- An NDA agreement was signed with Verizon.
- Verizon will assist NC-CAV with
    - Providing the technical support needed under Thrust 2 of the NC-CAV Center to investigate the communication needs for future CAVs
    - Providing the technical support and communication devices needed for the development of a CAV testbed
    - Providing communication devices for 5G connectivity of the vehicles

NC-CAV: Stakeholder Engagement Activities

Real-Time Innovations (RTI) is now onboard!

- NC-CAV and RTI started collaboration on reliable communication for CAV testbed
  - RTI's DDS-Connext provides Data Distribution Service (DDS) as an application for Internet of Things (IoT) to enable implementation of distributed network applications
  - RTI provided the NC-CAV team with Connext DDS software, which can be used as a middleware for developing the NC-CAV use cases to increase the reliability and communication efficiency
  - RTI provided NC-CAV team with training workshops introducing the basic functionality of Connext DDS and providing focused guidance and best practices to help the NC-CAV researchers to get started and to integrate Connext DDS and ROS
  - RTI also agreed to help the researchers in understanding how to use the rich set of RTI tools efficiently



NC-CAV: Stakeholder Engagement Activities

- **Siemens is now onboard!**

SIEMENS

- Siemens is sponsoring the NC-CAV Center by providing the software products
  - TASS PreScan

  - Conversation is going on with Siemens to make Aimsun available to the NC-CAV researchers as well

NC Transportation Center of Excellence on Connected and Autonomous Vehicle Technology (NC-CAV)

Sustainability Activities

NC-CAV Sustainability Activities

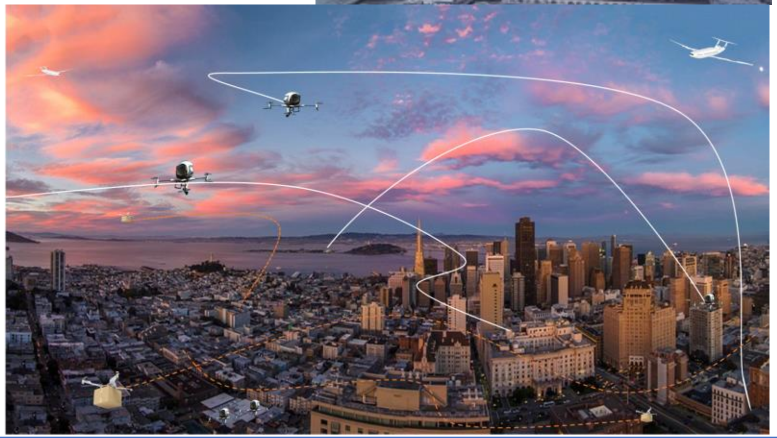
Effort sare being directed toward sustaining the Center’s research activities:

- Developing a Testbed of Connected Autonomous MicroTransit Vehicles, NSF, $785,000
- Excellence in Research: Real-time Fault Diagnosis for Self-Driving Vehicles, NSF, $1M
- University Leadership Initiative (ULI): Secure and Safe Assured Autonomy, NASA, $8M
- Methods to Transfer System Knowledge to Driver/Operators to Enhance and/or Accelerated Situational Awareness During Handoff, NHTSA (Pending)
- AI Institute: Customized Optimization for Real-world Problem Solving, NSF (Pending)

NC-CAV Sustainability Activities

A team of researchers from NC-CAV Center was awarded by NASA for a 4-year $8M ULI grant to develop Safe and Secure Assured Autonomy. From the NC-CAV Center, Dr. Homaifar will lead this new ULI program and Dr. Karimoddini will lead TC1 on Safe Perception, Coordination, Planning, and Navigation to develop flexible and adaptive coordination and control algorithms for **Urban Air Mobility (UAM)**.

- **TC1: Safe Perception, Coordination, Planning, and Navigation** will develop flexible and adaptive coordination and control algorithms for Urban Air Mobility (UAM).
- **TC2: Secured Autonomy** will develop secure algorithms for future UAM. Cyber-physical characteristics will address both conventional data security and physical security.
- **TC3: Verification and Validation and Testing and Evaluation** will develop verification and validation procedures to provide provable guarantees of correctness of the UAM software and support certification of the developed technologies through testing and evaluation.
- **TC4: System Integration** will integrate TC 1-3 products through dependency analytics, integrated simulation, and experimental flight tests through fast-learning cycles.



NC-CAV Sustainability Activities

A team of researchers from NC-CAV Center was awarded by NSF for $1M to develop Real-time Fault Diagnosis for Self-Driving Vehicles. Drs. Karimoddini and Homaifar will serve as the PIs in this project.

- **Objective 1**: Develop domain-specific fault detection techniques: The PIs will develop fault detection mechanisms in three domains: data, discrete events, and computation.
- **Objective 2**: Demonstrate Cross-Domain Fault Detection: The PIs will collect, analyze, and combine signatures from the three domains to improve fault detection.
- **Objective 3**: Create Cross-Domain Fault Injection/Detection Testbed

NC-CAV Sustainability Activities

- A research team from NC-CAV Center was awarded by NSF for $550k for “Acquisition of a Testbed of Connected Autonomous MicroTransit Vehicles”.

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Thank you for your support to NC-CAV!

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